Investigation of the Natural Sand Transport on the Belgian Continental Shelf

BUDGET
(Beneficial usage of data and geo-environmental techniques)

SUSTAINABLE MANAGEMENT OF THE NORTH SEA

SCIENTIFIC SUPPORT PLAN FOR A SUSTAINABLE DEVELOPMENT POLICY

FEDERAL OFFICE FOR SCIENTIFIC, TECHNICAL AND CULTURAL AFFAIRS (OSTC)
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Sustainable Management of the North Sea

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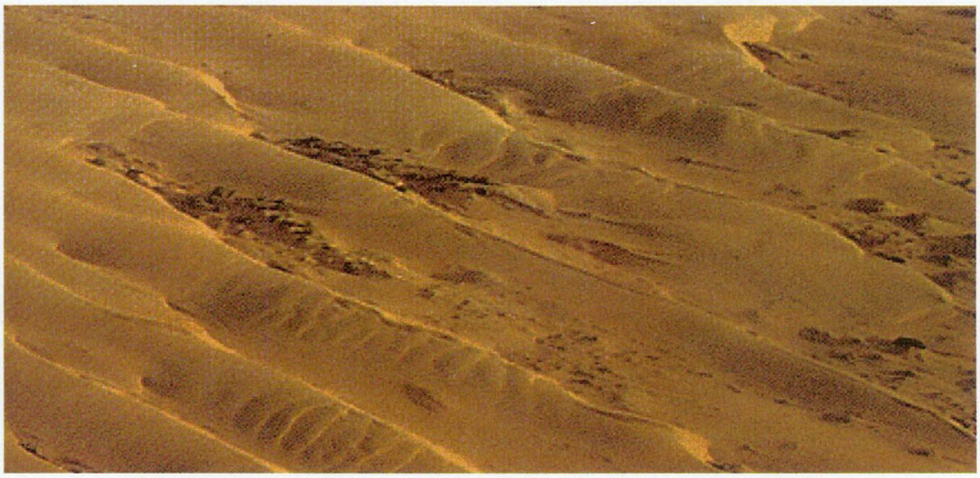

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INTRODUCTORY NOTE

This report presents the final results of the BUDGET project (Beneficial usage of data and geo-environmental techniques), which aimed at a compilation and critical analysis of all available information regarding the natural sand transport on the Belgian continental shelf (further abbreviated as BCS).

The scientific work mainly consisted of integrating geological, morphological, sedimentological, hydrodynamical and sediment transport data and therefore the following partnership was set-up:

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Given its objectives, BUDGET was primarily a desk study; still supplementary initiatives were undertaken which highly improved the final results.

A major output became the synthesis map on the natural sand transport on the BCS. This map largely benefited from additional survey work that was carried out in the Hinder Banks region. With the help of the oceanographic vessel 'Belgica', two reconnaissance surveys were set-up using state-of-the-art techniques. In this framework, Samuel Deleu deserves a special appreciation for upgrading this data set into a seabed mobility study and illustrating the possibilities of integrated research on the BCS.

An important scientific input could be achieved by the collaboration of different researchers who were invited to workshops organised in the framework of the project. The first workshop was held on October 26-27th 2000 to discuss the first results of the BUDGET project and in particular the sediment budgeting aspect. A second workshop was held on October 26th 2001 to present the final results and discuss state-of-the-art and future research. We wish to thank these researchers who spent some of their valuable time with us and for their collaboration:

Prof. Dr. Michael Collins (University of Southampton (UK), School of Ocean & Earth Science)
Drs. Alex Bastos (University of Southampton (UK), School of Ocean & Earth Science)
Prof. Dr. Alain Trenteseaux (Université de Lille (FR), Laboratoire de Sédimentologie et Géodynamique)
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Dr. Robert Vos (Universiteit Amsterdam (NDL), Instituut voor Milieuvraagstukken)
Dr. Sandra Passchier (TNO-NITG (NDL))

We wish to acknowledge and thank as well following persons, research and government institutions who shared with us their data concerning all aspects of the Belgian continental shelf: Belgian Navy, Belgian Geological Survey, Dutch Naval Office, Ghent University - Marine Biology Section, Ghent University – Research Unit for Marine and Coastal Geomorphology, Jan Tytgat, TNO Geo Marien en Kust (The Netherlands) and the University of Lille (France).

The Ministry of Economic Affairs – Marine Sand Fund is greatly acknowledged for providing additional data and for the use of the multibeam system installed on the 'Belgica' including the processing possibilities.

The additional survey work largely benefited from the help of the officers and crew of the 'Belgica'. With them, quite some colleagues and students are thanked for their cooperation.

Special thanks are finally due to the Ministry of the Flemish Community, Administration Waterway, Infrastructure and Nautical Affairs, Waterways and Coastal Section for providing us with an extensive bathymetric data set and allowed us insight in its numerous reports on sediment dynamic problems.

We wish as well to thank the Federal Office for Scientific, Technical and Cultural Affairs who supported BUDGET and for their thrust in this project.

The BUDGET partners — December, 27th 2001

Reference to this report:

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ABSTRACT

On the Belgian continental shelf (BCS), a variety of sediment dynamical studies have been performed both by governmental organisations and research institutions. Each study proposed to achieve a better insight in the sediment dynamical processes taking place on a specific spatial scale and during a particular time period. However, all these studies contain a piece of information, which contribute to the global sediment dynamical behaviour of the sediments of the BCS.

In the course of the project, an overview has been produced of all these studies. Most of the data has been re-evaluated and the results were compiled in a synthesis map to characterise the natural sand transport on the Belgian continental shelf. The map indicates the general nature of the surficial sediments superimposed with the occurrence of larger bedforms. Additionally, areas are indicated where the thickness of the quaternary deposits is less than 2.5 m as these sediments might take part in the sediment transport process. To illustrate the hydrodynamics of the BCS, current ellipses have been selected based on modelling results on a 750 m grid resolution and locations were indicated where current meter or other hydrodynamic data has been collected. Towards the directions of sediment transport, a variety of arrows are drawn whereby a distinction is made between transport vectors based on geo-environmental methods and those based on in-situ sediment transport measurements and on modelling results. If available, quantities are added uniformised in tonnes/m/day.

The study also included a critical analysis of the data and methods used. The deduction of residual transport directions was evaluated on the basis of the asymmetry of bedforms, tracer experiments, sediment differentiation, current and suspended sediment concentration measurements and based on numerical sediment transport modelling. Evaluation criteria were set-up regarding the different space and time scales involved. The influence of hydro-meteorological conditions on the sediment dynamics was discussed.

The results allowed defining gaps in the present knowledge and including recommendations for future research and propositions for an integrated research programme on the Belgian continental shelf. Main emphasis is put on an efficient mapping of the seafloor including the set-up of an automated characterisation of seabed sediments albeit combined with a suitable sampling strategy. Regarding hydrodynamical and sand transport measurements, the development of a multi-sensor bottom frame is recommended including a realistic quantification of sediment fluxes through the water column.

To enhance the efficiency and practical use of seabed data, the set-up of an overall *Geographical Information System* (GIS) is highly recommended including guidelines and protocols on the prerequisites of mapping and sampling projects since this would largely facilitate the set-up and evaluation of environmental impact assessments.

The project largely benefited from contributions from foreign researchers from France, England and the Netherlands.

1. INTRODUCTION

The BUDGET project aims at an assessment and an understanding of the residual sediment transport on the Belgian continental shelf (further abbreviated as BCS) and this on different time and spatial scales.

This assessment is to be based on a compilation of available information followed by a critical analysis of the data in which results from different methods such as modelling and a large number of sediment dynamic techniques based on fieldwork are compared.

Answers will be sought for a number of basic questions such as:

- *Which are the main bedload transport pathways on the BCS?*
- *Which processes cause the sediment transport and what is the influence of external factors such as storms and wind on the tide-induced transport?*
- *Can a realistic sediment budget be calculated for the BCS?*
- *Is there any evidence for the existence of sediment sinks and sediment erosion areas on the BCS?*

Answers to all these questions have not only a scientific interest, but they are as well indispensable in the framework of environmental policy plans especially regarding aggregate extraction and relocation operations of dredged material.

Offshore aggregate extraction is becoming each year more important as land reserves of good quality sand become rather scarce. On the BCS, aggregate extraction is presently allowed in 2 zones (Figure 1). Concession zone 1 includes the Goote Bank and the Thornton Bank both belonging to the Zeeland Ridges; whilst the Flemish Banks Oostdijck, Buiten Ratel and the Kwinte Bank are within the concession zone 2. The exploitation of these banks is coupled to a multidisciplinary monitoring programme including a sequential follow-up of the surficial sediments and morphological changes (MINISTERIE VAN ECONOMISCHE ZAKEN (1999)). A synthesis of the effects of the sand extraction on the marine environment is presented in RZONZEF (1993) whilst DE MOOR & LANCKNEUS (1992) discuss the extraction of sand and gravel including the physical monitoring and the possible effects regarding seafloor stability.

However if offshore aggregate extraction is to become a sustainable operation, it is important not only to monitor the effects of the extraction on the seabed topography but also to analyse the dynamics of the sand fluxes. Moreover, knowledge is sought on the source of the new sediment and to investigate whether this supply does not involve some erosion process in the nearshore area or elsewhere. Furthermore, the sandbanks are an important link in the dissipation of wave energy towards the coast. A major extraction could in this case lead to a re-distribution of areas with increased wave energy what could induce increased coastal erosion.

Similarly, a better understanding of the residual sediment dynamics is essential in the definition of new dumping grounds of dredged material. This knowledge can avoid the implementation of dumping grounds in these areas where the dominant residual transport directions point to the area of origin of the dredged material.

A scientific well-founded study of the seafloor sediments and of the dynamic processes, including the mobility and transport of sediment, is a necessity for each country bordering the sea. The aim of the BUDGET project is to present a comprehensive picture of the extent and limitations of our knowledge for the BCS.

The authors realise that the present work only represents a starting document on which further research can be based and that this first evaluation of available information will undoubtedly have to be updated many times in the future.

2. MATERIALS AND METHODS

The BUDGET project was essentially meant to be a compilation study on the natural sand transport research on the Belgian continental shelf. In that sense a large effort was made in collecting all available information concerning the sedimentology, the geology, the morphology, the sediment dynamics and the hydrography of the BCS. However, once this inventory of all data started, it became clear soon that the end product would be of a much higher scientific interest if the compilation work could be based on the original digital (or analogue) data of the different research and government institutions. Several of these institutions agreed under certain conditions that their data could be used in the framework of the BUDGET project. The use of the original data, like for example grain-size data, led to additional work but this approach had the advantage that data could be processed and compared in a much more dynamic and flexible way.

During the project, two workshops were held during which a number of scientists from the neighbouring countries, active in the same field of research, could be invited. From a scientific point of view, it was extremely useful to discuss with these scientists the progress of the BUDGET project. This co-operation on an international level acted as a sounding board and allowed an update of information and an exchange of experience regarding the use of old and new techniques which undoubtedly enhanced the scientific level of the project and guaranteed at the same time a global quality control.

No fieldwork was included in the original proposal. However during the two years of the project, the results of a number of field activities could be integrated in the final project results. It became very clear from the beginning of the project that most of the compiled data was localised in the near coastal area and that very little information was available in the more offshore sections of the BCS (such as the Hinder Banks area). A series of sampling operations and multibeam recordings in some of these sections made it possible to fill in some important gaps.

3. RESULTS

3.1. Characterisation of the Belgian continental shelf (BCS)

3.1.1. Introduction

The Belgian continental shelf is characterised by a number of sandbanks that can be grouped as Coastal Banks (Nieuwpoort Bank, Stroombank, Wenduine Bank), Flemish Banks (Oostdyck, Buiten Ratel, Kwinte Bank, Middelkerke Bank Oostende Bank), Hinder Banks (Fairy Bank, Westhinder, Noordhinder, Oosthinder, Bligh Bank) and the Zeeland Ridges (Thornton Bank, Goote Bank, ...) (Figure 1). The Coastal Banks and the Zeeland Ridges are quasi parallel to the coastline, whilst the Flemish and Hinder Banks have a clear offset in relation to the coast.

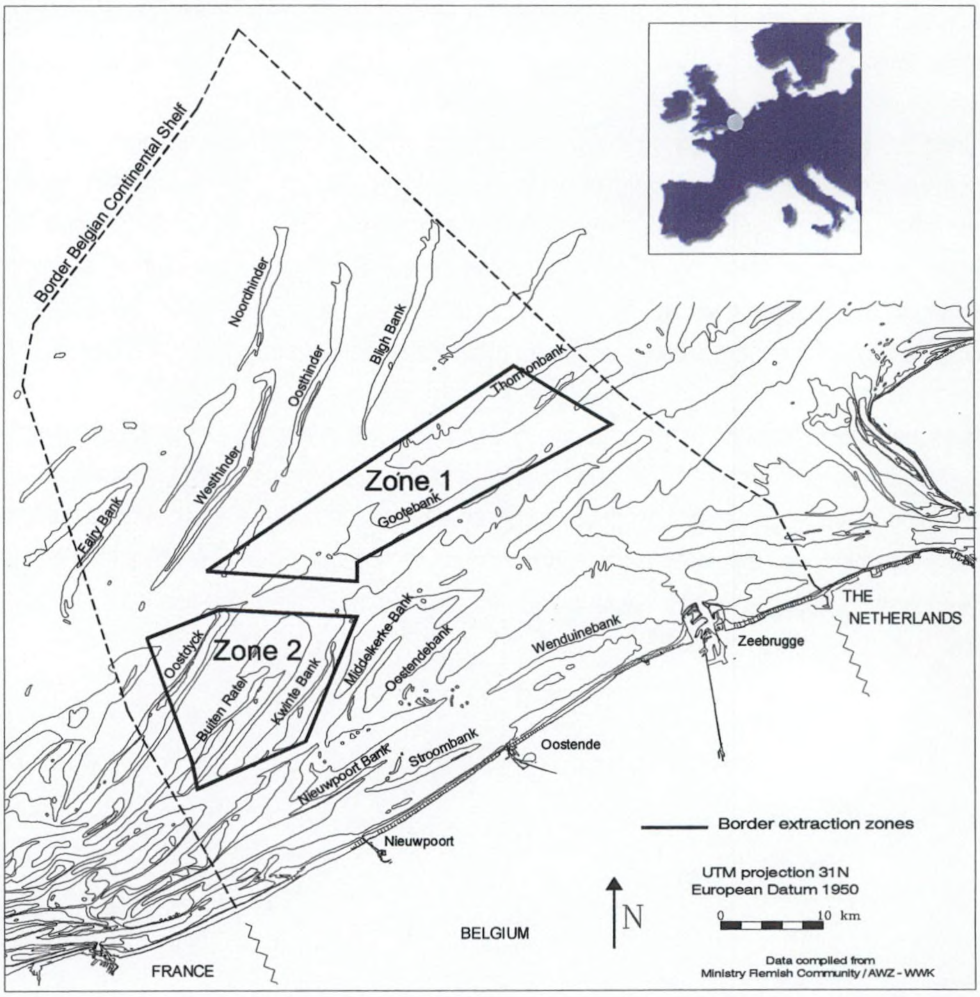

Figure 1. Bathymetry of the BCS with an indication of the present areas of aggregate extraction (data from the Ministry of the Flemish Community, Waterways and Coastal Section).

In the following paragraphs, an overview is given of the different aspects related to the characterisation of the natural sand transport on the BCS. Reference is also made to VAN LANCKER et al. (2001) discussing the occurrence of sandy deposits on the BCS.

3.1.2. Geological framework

The Quaternary and Tertiary of the BCS have been primarily mapped for the Ministry of Economic Affairs. BASTIN (1974) and DE BATIST (1989), DE BATIST and HENRIET (1995) mapped the subcrop pattern of the Tertiary Formations (Figure 2). The offshore Quaternary deposits have been mainly studied by and for the Belgian Geological Survey. DE MAEYER et al. (1985) and WARTEL (1989) have focussed on the Quaternary of the western coastal banks. DE MOOR (1985) studied the substratum of the Kwinte Bank using sub bottom profiling and Rokleng drillings. Also, on the basis of sub bottom profiling DE MOOR & LANCKNEUS (1992) investigated the internal structure of the Goote Bank.

During the MAST projects Resecused (DE MOOR and LANCKNEUS (1993)) and Starfish (HEYSE and DE MOOR (1996)), the Quaternary of the Middelkerke Bank was studied in detail. This research clarified that the quaternary up-building of the Middelkerke Bank is not merely an up-piling of sand, but a result of different well-distinct phases. Subsequently, the sediments involved can be very diverse in nature and vary from clay to coarse sands and gravel. However, only the upper sediment cover (in this case 7 to 13 m thick) is representative of the present hydrodynamic regime (TRENTESAUX et al. (1993); BERNE et al. (1994); TRENTESAUX et al. (1999)).

In the area of the Flemish Banks and the Hinder Banks, the Tertiary substratum is mainly composed of the Kortrijk Formation (Ieper clay) whilst to the east, the Formations of Kortrijk, Gent, Aalter, Maldegem and Zelzate occur.

In the framework of this project emphasis was put on the localisation of areas where the thickness of the Quaternary is minimal or where the Tertiary substrate is locally being eroded as these sediments might take part in the sediment transport process. From seismic investigations MARECHAL and HENRIET (1983) and MARECHAL and HENRIET (1986), it was deduced that the thickness of the Quaternary is less than 2.5 m in most of the swales of the BCS (Figure 2). In the near coastal area, the Kortrijk Formation is locally being eroded in the Westdiep geul, whilst towards the east the clays of the Maldegem Formation (e.g. Scheur) arise. In the Flemish Bank region, tertiary deposits might be eroded in the swales west of the Kwinte Bank. Further offshore, especially the swale areas of the southern part of the Hinder Bank region have a thin quaternary cover and are often characterised by a gravely floor. To the south and northeast of the Goote Bank, no quaternary deposits are found.

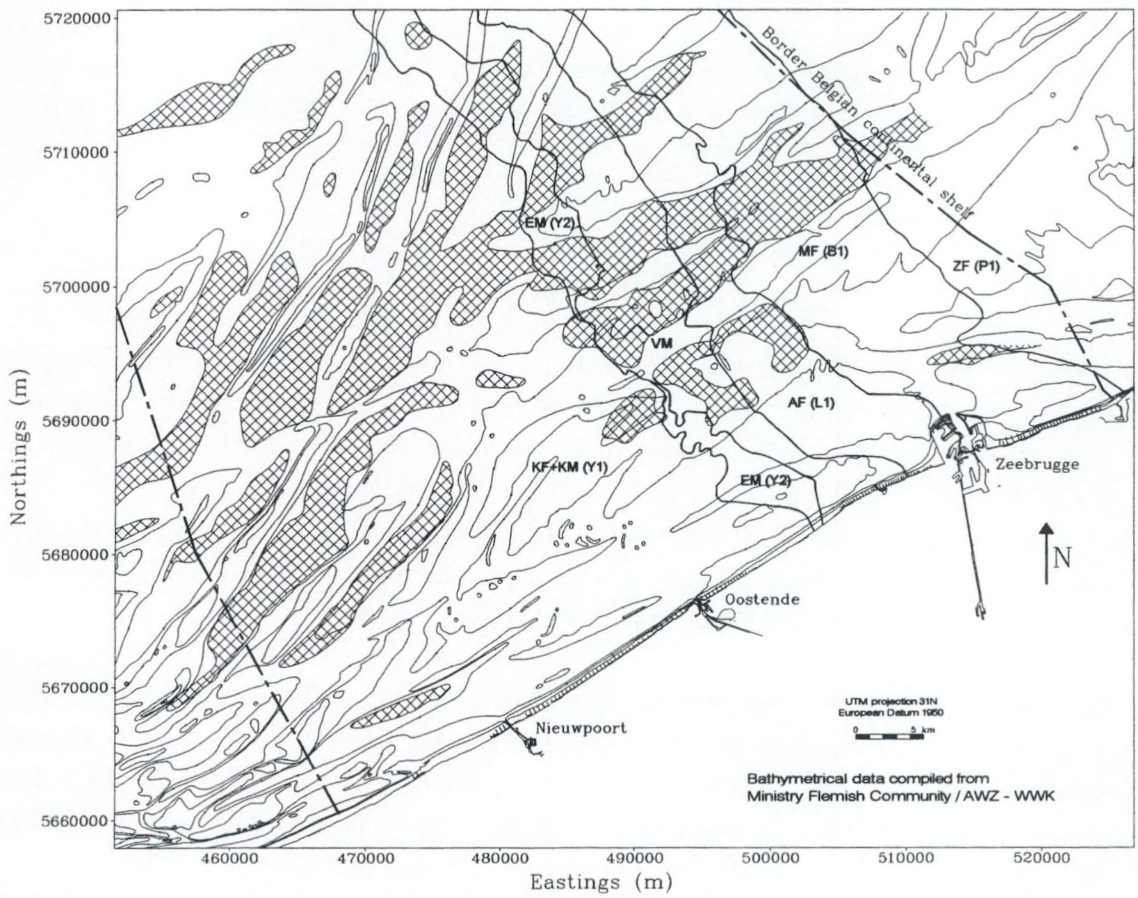

Figure 2. Subcrop pattern of the Palaeogene offshore seismic-stratigraphical units (DE BATIST and HENRIET (1995)) superposed by a delineation of areas where the quaternary cover is less than 2.5 m (hatched zones) (ZF: Zelzate Formation, MF: Maldegem Formation (mainly clay), AF: Aalter Formation, VM: Vlierzele Member, MPM: Merelbeke and Pittem Members, EM: Egem Member, KM: Kortemark Member, KF: Kortrijk Formation (mainly clay)). Background bathymetry: Waterways Coast Division (VAN LANCKER et al. (2001)).

3.1.3. Morpho- sedimentological characterisation

<u>Introduction</u>

The morpho-sedimentological characterisation of the BCS included the compilation of morphological and sedimentological data in order to give evidence of areas with a high sediment transport potential. To accomplish this aim emphasis was put on the occurrence of larger bedforms as they are formed under a higher current regime and are usually associated with areas having a significant sediment input. In this framework it was also important to know the sediments involved and hence a compilation of sedimentological data was a necessity. The basis of a morpho-sedimentological characterisation is a detailed bathymetrical map. To compile such a map, data was obtained and reprocessed from the

Waterways and Coastal Section of the Ministry of the Flemish Community (Figure 1). For the northern part of the BCS, the Dutch Naval Office provided additional data, but still the whole of the BCS is not covered.

Figure 3 is a digital terrain model of the Belgian Continental Shelf compiled on the basis of single-beam bathymetrical data from the Waterways and Coastal Section of the Ministry of the Flemish Community. This map provides valuable information on the occurrence of bedforms and their interrelationships. Remarkable is the highly dynamic nature of respectively the northern and western extremities of the Flemish Banks and the Zeeland Ridges. At some locations (a.o. halfway the Westhinder; near the Goote Bank, Kwinte swale), the morphology of the Top Tertiary (LIU et al. (1992)) substratum can be seen.

Morphological characterisation

To present a global overview of the presence and characteristics of the bedforms on the BCS, a compilation was made of all available bedform information. The research focussed on the occurrence of large dunes (sandwaves) as information concerning small to medium dunes (megaripples) is scarce and their small size makes detection with classic acoustical survey techniques very difficult. The information on bedforms that was collected came from publications, side-scan sonar surveys and single- and multibeam registrations.

Single-beam bathymetric recordings have been extensively used for the study of bedforms on the BCS (both by and for the Waterways and Coastal Section) and by research institutions (i.e. Research Unit Marine and Coastal Geomorphology of Ghent University). In the framework of the PhD thesis of HOUTHUYS (1990) mainly the Buiten Ratel was investigated whilst VAN LANCKER (1999) monitored the bedforms in the western near coastal area (comprising the Nieuwpoort Bank, Stroombank, Baland Bank, southern part of the Middelkerke Bank, Ravelingen and the swales Grote en Kleine Rede) during a 4-years observation period.

Side-scan sonar recordings were carried out in the past on different sections of the BCS. Mostly, the analyses were restricted to small areas that were studied in detail. However, the investigations carried out on the Middelkerke Bank involved a side-scan sonar survey of the entire bank and proved to be extremely useful (LANCKNEUS and DE MOOR (1994)). VAN LANCKER (1999) obtained side-scan sonar imagery in the western part of the coastal zone and recently detailed side-scan sonar mosaicing was performed in the OSTC HABITAT project (DEGRAER et al. (2000)) covering the western coastal zone. Since 1999, the follow-up of the sandbanks under extraction is carried out using a multibeam echosounder (Simrad 1002S) installed on the Belgian oceanographic vessel RV 'Belgica'. On the basis of 'full coverage' multibeam recordings, highly accurate digital terrain models are being produced. Figure 4 is a digital terrain model of the Kwinte Bank and presently data from the Thornton Bank is being processed (Marine Sand Fund, Ministry of Economic Affairs).

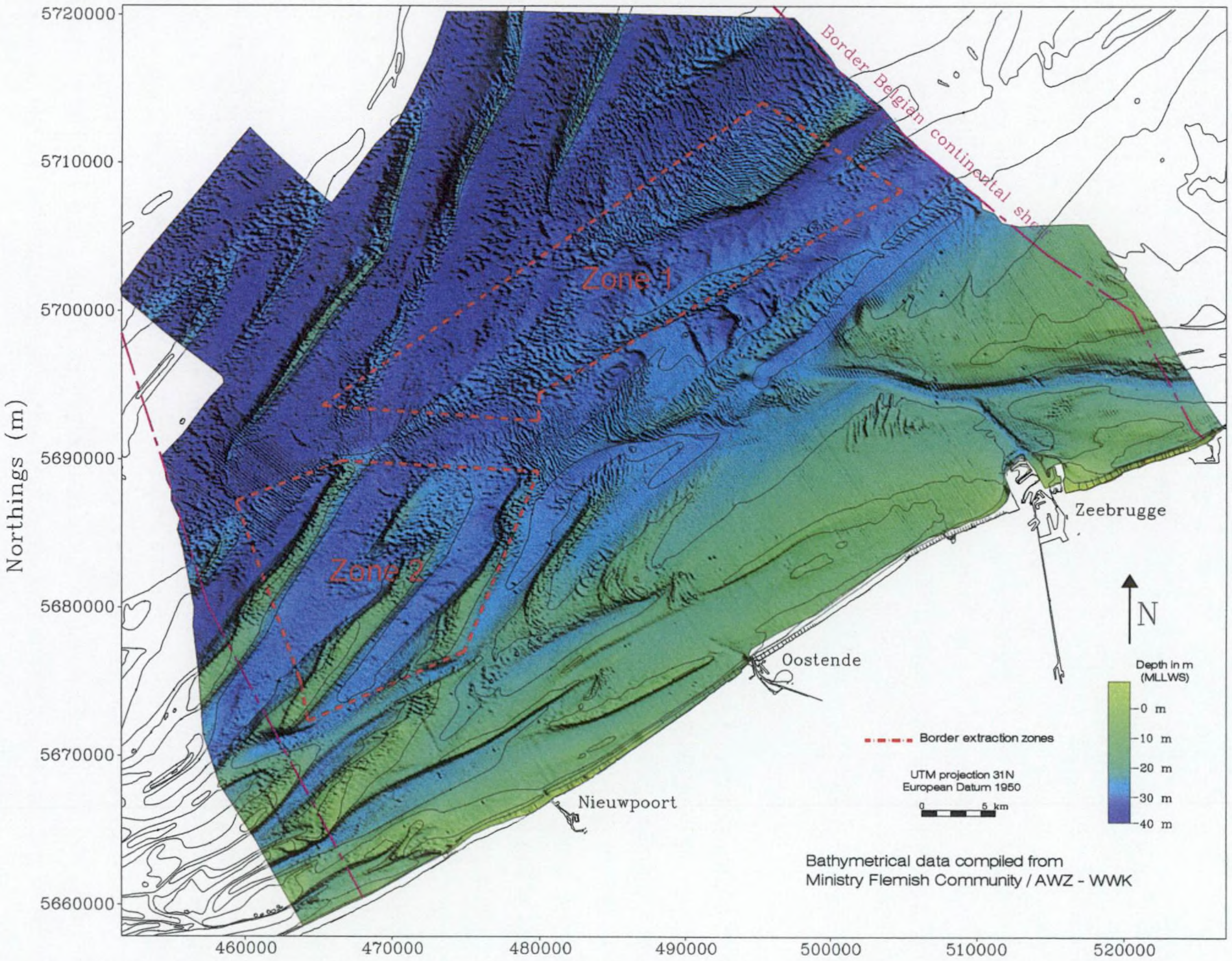

Figure 3. Digital terrain model of the Belgian Continental Shelf compiled on the basis of single-beam bathymetrical data from the Waterways and Coastal Section of the Ministry of the Flemish Community.

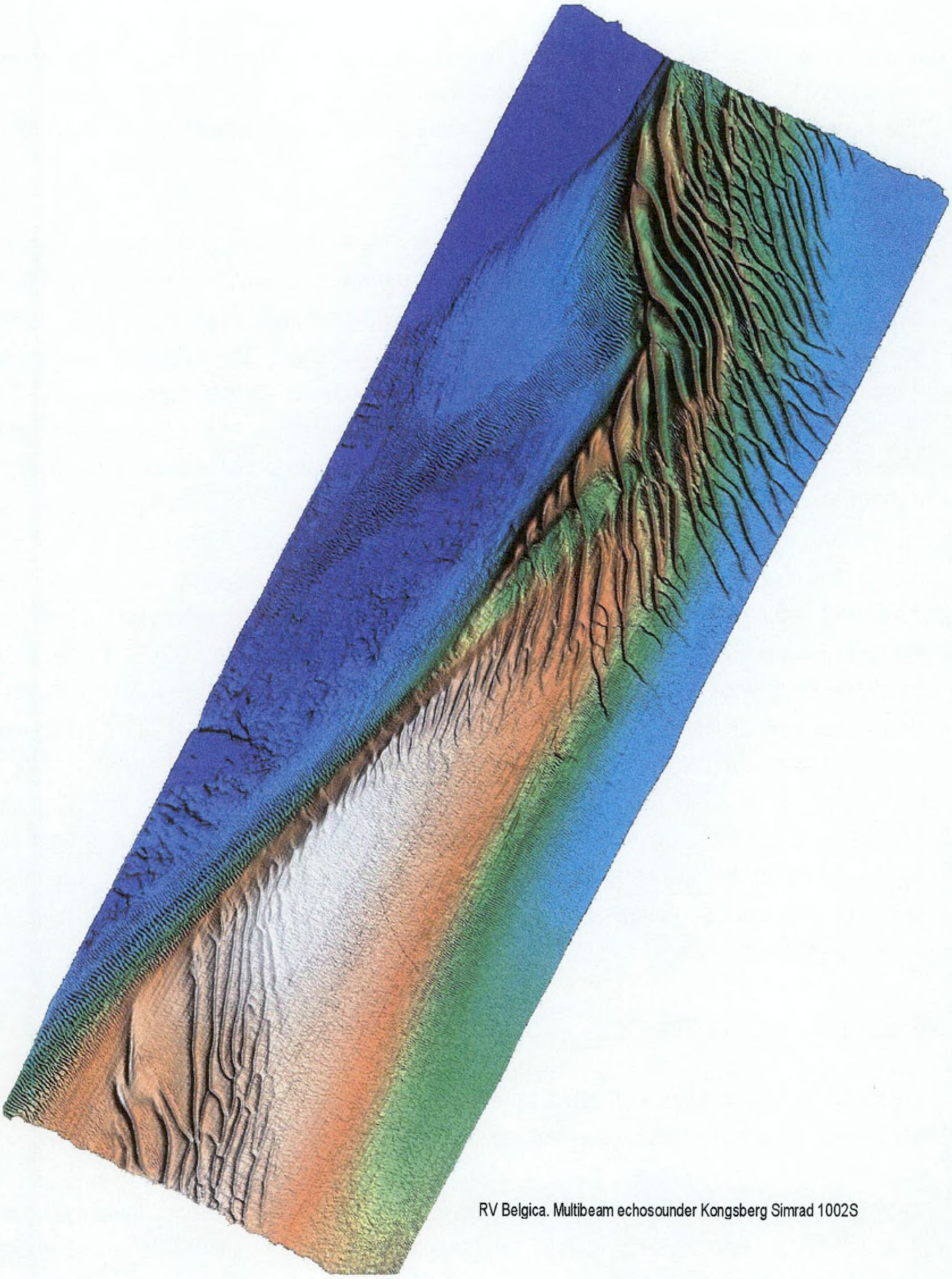

Figure 4. Digital terrain model of the Kwinte Bank (Marine Sand Fund, Ministry of Economic Affairs)

Within the scope of the present project, a multibeam reconnaissance survey has been carried out in the Hinder Banks region as bedform data in this area was scarce. On the basis of 2 km spaced multibeam recordings, DELEU (2001) mapped 956 large dunes occurring as well on the sandbanks as in the swales. The latter is quite remarkable as up till now, it was thought that large dunes were merely constraint to the sandbanks.

On the synthesis map (Annex 2), the distribution of the large dunes is indicated and if sufficient dimensional data was available, fields of height classes were drawn. The asymmetry of the dunes is discussed later as this provides an indication of the residual transport. Large dunes, 2 to 4 m in height, are generally present in the offshore area where they are mostly superimposed on the sandbanks (LANCKNEUS and DE MOOR (1994)). Figure 4 illustrates best their appearance as it gives the distribution pattern of the bedforms over the whole Kwinte Bank (Marine Sand Fund, Ministry of Economic Affairs). Noteworthy is the amalgamation of the dunes at the northern part, which is clearly superior over the dunes occurring along the steep slope of the sandbank. Generally, the highest dunes are observed at the northern extremity of the Flemish Banks (up to 8 m) and in the northern part of the Hinder Banks region. Higher dunes are also observed at kinks that are often observed along sandbanks. Fields of large dunes also occur at the western extremity of the Goote Bank and in the northern part of the Hinder Banks region where they were abundantly observed in the swales (up to 11 m) (DELEU 2001). Closer to the coast their occurrence is merely restricted and the sandbanks are generally devoid of bedforms. Fields of large dunes were observed in the Westdiep - Broers Bank coastal system (VAN LANCKER et al. (2000)), in the interaction zone of the Nieuwpoort Bank, Stroombank and Baland Bank (VAN LANCKER (1999)), the Ravelingen (DELGADO BLANCO (1998)), along the Wandelaar (VANSTAEN (in prep.)) and north of the Paardenmarkt shoal (CHARLET (2001)). Their height exceptionally exceeds 2 m. Remarkably, the highest dunes are sometimes found in the shallowest areas. A discussion on their occurrence can be found in Paragraph 3.3.1. Referring to Figure 3, much more fields of large dunes occur, but up till now they haven't been studied in detail.

Sedimentological characterisation

In order to be able to relate the natural sand transport on the BCS to the in-situ sediments, an inventory has been made of the available sedimentological information.

It is clear that the nature and differentiation of the surficial sediments is related to the unique configuration of the sandbank-swale systems whereby the interaction of the current with the large-scale morphology is responsible of a hydraulic sorting of the sediments. The sand fraction (0.063 to 2 mm) preferentially takes part in the up-building process of sandbanks whilst the coarser sands, gravel (> 2mm) and the silt-clay fraction (<0.063 mm) are merely found in the swales. Depending on the hydrodynamical characteristics, fields of large dunes locally occur that are often dynamic in nature and composed of coarser sandy sediments.

The gravely deposits in the swales are merely relict sediments that are hardly moved by the present hydrodynamic regime and therefore it should be evaluated whether they are a renewable sediment source or not. Generally, the finest sediments can only deposit in the deeper swales, but studies in the near coastal area showed that muddy deposits can occur up to a depth of – 6 m MLLWS related to a high availability of fine suspended matter. Shallower, this fraction is washed out by an interplay of currents and waves (VAN LANCKER (1999)). On the scale of the BCS, the surficial sediments generally coarsen in an offshore direction.

In the following paragraphs a literature overview is given of the existing sedimentological studies and this on as well a large- as on a small-scale basis.

BASTIN (1974) gave an overview of the history of the lithological mapping (e.g. VAN MIERLO (1899); GILSON (1900, 1907, 1924); VAN VEEN (1936) & HOUBOLT (1968) with the most important maps, and provided a map on the surficial sediments of the near coastal area. After the work of BASTIN (1974), sedimentological maps have been drawn, but mainly for internal purposes (MINISTERIE VAN OPENBARE WERKEN (1976-1982 and 1984-1986)). CEULENEER and LAUWAERT (1987), D.E.R. Ostend (1988) give a synthesis and published maps of the surficial sediments of the Flemish Bank area based on the 1400 samples from the national program "Project Zee" (GULLENTOPS et al. (1977)), but added with numerous samples provided by the University of Ghent and the Katholieke Universiteit Leuven, some private firms (e.g. Haecon) and the Ministry of Agriculture after 1976. In 1988, the Belgian Geological Survey reported a map of the surficial sediments of the coastal zone based on 564 samples. In a publication of the Ministry of the Flemish Community (MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1994)) an update of the synthesis on the available data is given together with a map of the surficial sediments along the west coast (CEULENEER and LAUWAERT (1987) and a variety of sources in the period 1962-1977) and along the east coast (MOW – HAECON 1984-1986). On a scale of 1:250000 a map was published of the Holocene and surficial sediments through a cooperation with the British, Dutch and Belgian Geological Survey (BALSON et al. (1991)). However, this map shows major hiatuses especially in the Hinder Bank region and along the West Coast. GULLENTOPS & MALHERBE (1996) give an approximation of the grain-size distribution over the whole BCS.

On a somewhat smaller scale, but still including several sandbanks and swales, VAN LANCKER (1999) provides a map of the surficial sediments of the western near coastal area and the transition zone to the Flemish Banks. On a sandbank level several maps exist mostly in the framework of the monitoring of the sand extraction on the Belgian shelf (i.e. WESTBANKI/II/III project, Research Unit for Marine and Coastal Geomorphology) and for research purposes (e.g. LANCKNEUS (1989); HOUTHUYS (1990)). Noteworthy, is the MASTII Resecused project (DE MOOR and LANCKNEUS (1993)) in which the surficial sediments of the whole Middelkerke Bank were mapped in detail and published as a map. Recently, sediment information has been compiled for the area east of Zeebrugge (CHARLET 2001) and DELEU (2001) drew a sediment map for the Hinder Bank region. Within the OSTC project HABITAT, the surficial sediments of the western Coastal Banks were mapped in detail (HONEYBUN (1999), RENNIE (2000), DEGRAER et al. (2001)).

The Marine Sand Fund group of the Ministry of Economic Affairs is mainly mapping the surficial sediments of the sandbanks within the concession zones.

However, the sediment parameters upon which the above-mentioned maps are based are often diverse and hence a compilation of several maps is not straightforward. Moreover, most of the sedimentological data on the BCS is scattered and have been obtained in the framework of monitoring studies (e.g. MUMM, Department of Marine Biology of Ghent University). Since those samplings are merely restricted to one location, their integration is often extremely difficult. Moreover, the analyses are carried out using a variety of methodologies and statistical approaches. Therefore, several research and government institutions have been contacted to inform whether their sedimentological data could be used in the framework of this project (ref. Materials and Methods). Within the scope of the present project, these data have been used to draw a map of the sandy surficial sediments in view of the characterisation of the natural sand transport on the BCS and have been incorporated as background of the synthesis map (Annex 2).

In the following paragraph, a short description is given of the surficial sediments of the BCS based on studies that take into account the areal distribution of the surficial sediments and their nature in terms of their morphological position.

Coastal zone (up to 10 km offshore)

The coastal zone is generally characterised by fine sands (BASTIN (1974); DE MAEYER & WARTEL (1988)). Medium to coarse sands tend to occur in areas witnessing an intense seafloor-current interaction (e.g. funnelling effects) or due to anthropogenic influences. VAN LANCKER et al. (1997), studied the sedimentological variability of the coastal system between Nieuwpoort and Oostende also integrating the results of 124 boxcores taken in the framework of the MASTII Starfish project (STOLK (1993)). In HONEYBUN (1999), VAN LANCKER et al. (2000) and RENNIE (2000), the sedimentological nature of the area from the French Border up to Nieuwpoort is discussed. Although, many sediment samples were taken in the area of Zeebrugge (e.g. HAECON (1982a)), the results are difficult to integrate since they are largely biased by the extension works of the harbour. To evaluate the sediment dynamical nature of the area north of the shoal 'Paardenmarkt', 84 samplings were carried out in September 2000, and were compiled into a sediment map (CHARLET (2001)). The complex hydrodynamics and the local erosion of Tertiary clay give rise to the occurrence of as well clayey as coarse sandy sediments (up to a median grain-size of 500 µm). Regardless of the high variability, distinct sediment types could be distinguished. Presently, the surficial sediments of the Wenduine Bank area are being investigated (VANSTAEN in prep.).

The Flemish Banks

The surficial sediments of the Flemish Bank region are mainly studied in the framework of the monitoring of sand extraction within the concession zone 2 (DE MOOR (1984); DE MOOR & LANCKNEUS (1989); DE MOOR & LANCKNEUS (1991); DE MOOR & LANCKNEUS (1994); Marine Sand Fund, Ministry of

Economic Affairs). LANCKNEUS (1989) studied the surficial sediments of the Flemish Banks (Oostdijck, Buiten Ratel and Kwinte Bank and the swales) on the basis of 320 samplings (Van Veen grabs). Through cluster analyses it was shown that the grain-size generally coarsens from south to north with the coarsest sediments (rich in $CaCO_3$) found in the northeastern extremities of the banks. A coarsening is also found from the southeast to the northwest as well in the swales as on the banks with the coarsest sediments on the western flanks. Generally, the swales tend to be rich in gravel, $CaCO_3$ and the silt-clay fraction with the highest values centrally in the Negenvaam and Kwinte swale. Although the latter is characterised by the coarsest sand, most gravel is found in the Ratel swale.

Oostdijck en Buiten Ratel

- HOUTHUYS (1989) and HOUTHUYS (1990) investigated the sedimentary facies of the Oostdijck and the Buiten Ratel using a small Reineck boxcorer. Along the Oostdijck sandbank the median grain-size varied from 225 µm at the foot of the stoss slope up to 332 µm at the top and 366 µm along the foot of the steep slope. TYTGAT (1989) studied the gravely deposits in the Flemish Bank region. Towards the head of the Buiten Ratel, he was able to demonstrate a transport of fine gravel in a northeastern direction.

The Kwinte Bank

This sandbank is extensively studied in the framework of the monitoring of the sand extraction (Marine Sand Fund, Ministry of Economic Affairs). Published data mainly discusses the surficial sediments along the northern Kwinte Bank (84) (DE MOOR and LANCKNEUS (1992); VANWESENBEECK (1994):

- the finest sediment with a graphical mean less than 300 µm mainly occurs along the eastern slope of the bank (well-sorted), in the eastern swale (Negenvaam) and locally in the Kwinte swale;
- the western slope to top zone and the Kwinte swale is coarser (300-500 µm) with a poor sorting. Coarser sediment enriched with shelly material is found along the western slope along the northern extremity of the sandbank (up to 1500 µm);
- sediments are generally coarser along the top of the bank, and are less sorted;
- a strong variation of the sedimentological parameters is seen along the northeastern part of the sandbank;
- the highest silt-clay percentages are found towards the swales, to the southwest and east.

Middelkerke Bank

From TRENTESAUX et al. (1994) and O'SULLIVAN (1997) the following results are compiled:

- generally, fine to coarse sands occur with a median value of 175 to 884 µm;
- the $CaCO_3$-content varies from 8 to 47 % with the highest values in the shallowest areas;
- the grain-size generally coarsens from S to N and towards the slopes of the sandbank;
- along the top zone of the sandbank, coarse, carbonate-rich and poorly sorted sediments occur, the same holds true for the northern extremity of the bank and landwards of the southern extremity;
- deeper, finer sediments occur, often bioturbated and reduced;
- to the south, fine to medium sands occur with a CaCO3 content of 7 to 12%

Ravelingen

The Ravelingen is a small sandbank in the interaction zone of the near coastal area and the Flemish Banks and situated at the extremity of a flood-dominated swale (DELGADO BLANCO (1998); VAN LANCKER (1999)). The mean grain-size varies between 300 and 420 µm. The surficial sediments become finer towards the swales.

The Zeeland Ridges

Since the Goote Bank and the Thornton Bank belong to the concession zone 1, they have been mainly studied within the follow-up programme related to sand extraction. The surficial sediments of the central part of the Goote Bank are characterised by medium sands with a mean grain-size of 250 to 300 µm (VAN LANCKER (1993); LANCKNEUS et al. (1993)). In the swale north of the sandbank, sediments are coarser and locally enriched with gravel. The carbonate content varies from less than 10 % on the bank up to more than 40 % at the foot of the stoss slope.

Hinder Banks

On the basis of 65 samples in combination with an automated acoustical seafloor characterisation, DELEU (2001) discusses the surficial sediments of the Hinder Banks region in function of the main morphological entities. More sediment information is available, but merely as point observations. Generally, the area consists of medium sands with a mean grain-size of 300 to 420 µm that tend to coarsen in a northward direction. Gravel often occurs in the swales, especially to the south.

To conclude, it needs emphasis that, in most cases, the surficial sediments of a sandbank are subject to smaller scale grain-size differentiations in function of the morphological position.

VAN LANCKER (1999) studied the grain-size differentiation over 2 near coastal sandbanks and made the following observations:

- a washing out of sediments from the swales with an enrichment at the foot of the slopes of the sandbanks;
- along the stoss slope of the sandbank, a fining upwards trends can be observed;
- higher up the sandbanks, a coarsening is found with the coarsest grains being deposited along the steep slope of the sandbank

The trends were found along the whole sandbank and were confirmed for calm weather and after stormy conditions. The initial fining upwards trend is due to an enhanced interaction of the tidal currents with the sandbank whereby finer sand is gradually washed out and deposited slope upwards. The coarsening trend is due to the increasing action of the hydrodynamical agents with decreasing depths. In particular, the action of waves washes out the finer fractions and entrains the coarser grains. This means that waves take part in the maintenance mechanism of the sandbank and should not be seen as a pure erosive agent. Also VINCENT et al. (1998) postulated this regarding the Middelkerke Bank. The general coarseness of the steep slope of the sandbanks is due to the erosive action of the flood tidal current along this slope.

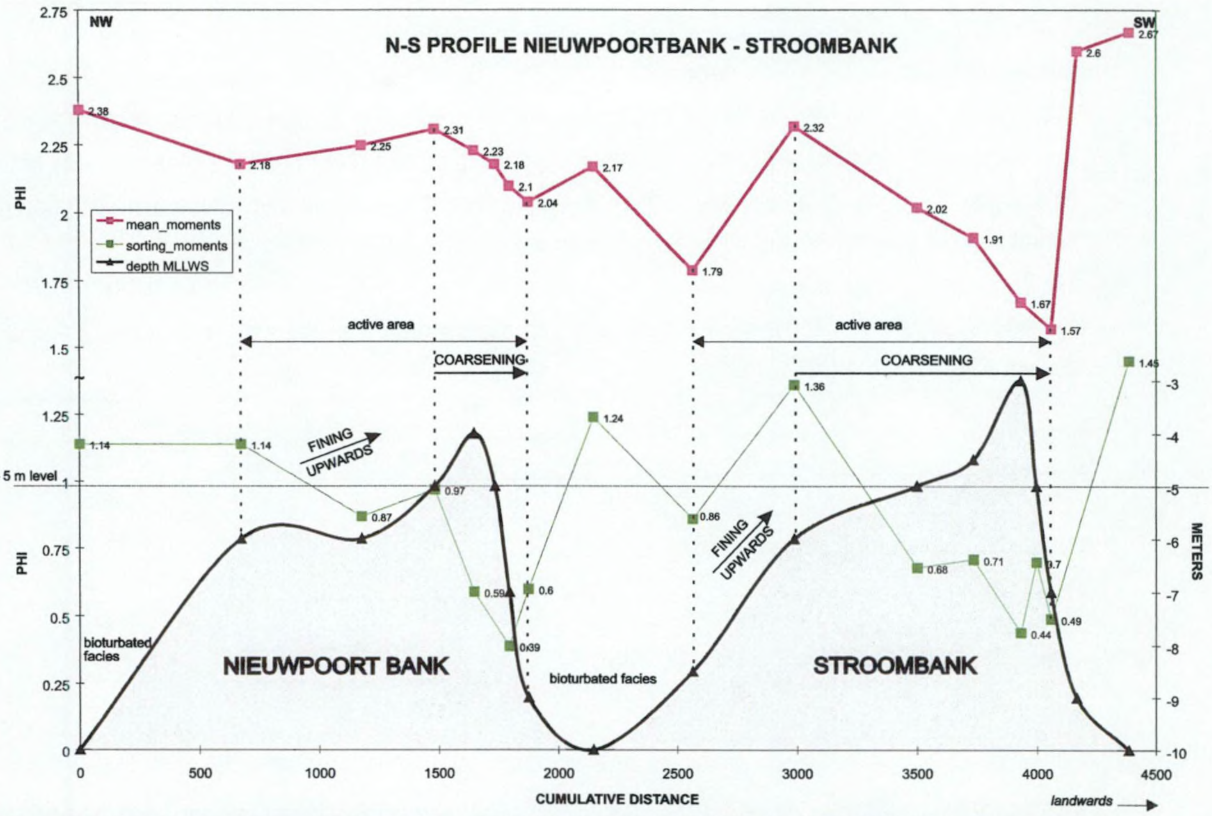

Figure 5. Grain-size differentiation over a sandbank (VAN LANCKER et al. (1997)) (Cumulative distance in m; Depth in MLLWS).

3.1.4. Hydrodynamics and sediment transport

Current measurements

Hydrodynamical information from long-term current measurements on the BCS is primarily obtained by or for Waterways and Coastal Section and MUMM. In the framework of the MAST projects Resecused (DE MOOR and LANCKNEUS (1993)), Starfish (HEYSE and DE MOOR (1996)) and CSTAB (O'CONNOR (1996)) an important set of information became available, albeit mainly restricted to the Middelkerke Bank area. Other hydrodynamical measurements are rather short-term and are related to specific research questions (MUMM (1995); MUMM (1997b); MUMM (1997a); VAN LANCKER (1999); LE COUTURIER et al. (2000); CHARLET (2001), DEGRAER ET AL. 2001)).

An overview of the current measurements carried out by MUMM Oostende in the period 1977-1995 is given in Annex 1 and are represented by a number on the synthesis map (Annex 2). A harmonic analysis of the tidal constituents in 8 of those stations was done by MOUCHET (1990).

In the framework of the CSTAB (Circulation and Sediment Transport Around Banks) project (O'CONNOR (1996)), the Proudman Oceanographic Laboratory (POL) performed OSCR-measurements on the

Middelkerke Bank area in the period 29/12/1992 till 28/01/1993. Those measurements were carried out every 20 min by two land-based radars and aimed at measuring surface currents. A harmonic analysis was performed on the original time series with 33 constituents. Table I gives the mean velocity of the long axis of the 5 biggest tidal ellipses. However, the current at the different locations can still show a large variation (i.e. between 37 and 75 cm/s for the long axis of the M_2 tidal ellipses).

Table I. Length of the mean, the minimum and the maximum of the long axis of the 5 biggest tidal current ellipses of the OSCR data.

Name	*Mean (m/s)*	*Min. (m/s)*	*Max. (m/s)*
M_2	0.6002	0.3681	0.7485
S_2	0.1550	0.0771	0.2289
M_4	0.1153	0.0647	0.1470
Z_0	0.1083	0.0460	0.1682
N_2	0.0985	0.0398	0.1361

Hydrodynamic numerical modelling

Hydrodynamic numerical modelling on the scale of the whole BCS is being performed by MUMM. The model relevant for the understanding of the current propagation over the whole BCS is implemented on a rectilinear grid and has a resolution of 25" x 40" (about 750 m x 750 m). Along the open boundaries, the model is using the output from the mu-STORM model, a 2D operational hydrodynamic model covering the North Sea and the English Channel. At the mouth of the Westerschelde, the model is coupled to a 1D hydrodynamic model of the Schelde estuary.

A near coastal zone hydrodynamical model using DELFT3D software has been developed at the Flanders Hydraulics Institute (HAECON (1999)). The latter enabled a nesting of a more detailed model of the Belgian East Coast (DE WIT (2001)). The resolution of the grid is about 50 m x 50 m near the coast up to 100 m x 700 m towards the offshore. Apart from current modelling, also waves were taken into account based on the SWAN model (Simulating Waves Nearshore) and the current-wave interaction.

On the synthesis map (Annex 2) a selection is made of current ellipses typically for a spring tide calculated from the 2D hydrodynamic numerical model mu-BCZ. Noteworthy, are the strongly rectilinear ellipses in the near coastal zone and in the mouth of the Westerschelde. Offshore and on the Vlakte van de Raan, the ellipses are more rotary in nature with a veering towards the sandbanks. At the northern limit of the BCS, the current ellipses are again more rectilinear. Additionally, the maximum current velocities were extracted from a spring tidal cycle and represented in Figure 6.

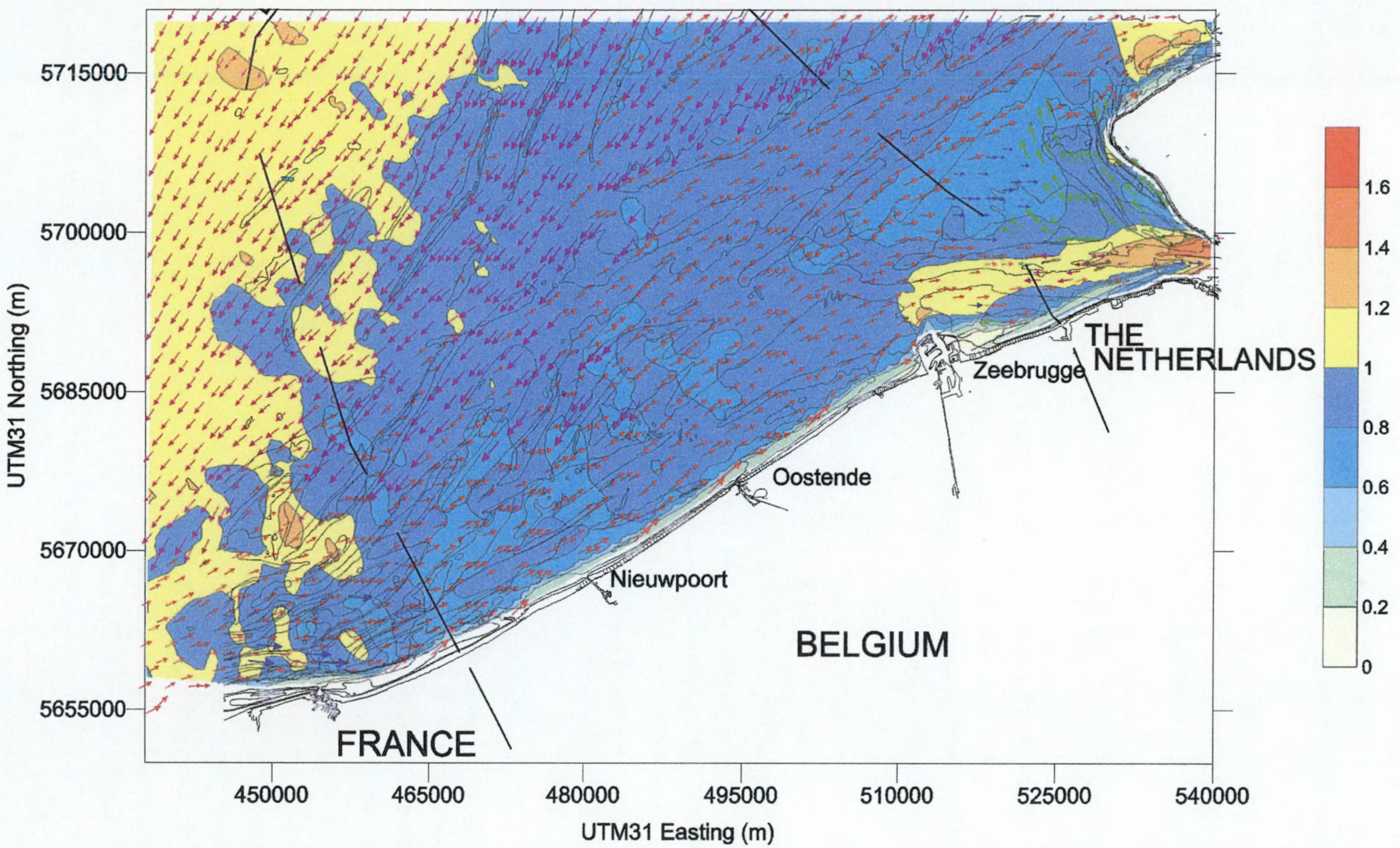

Figure 6. Maximum current velocities (m/s) along the BCS extracted from MUMM's mu-BCZ model. The coloured vectors group the direction of the current per quadrant.

Figure 6 shows that the tidal current velocities reach their maximum value during the flood (NE) in the near coastal zone and along most of the Flemish Banks region. The maximum current velocity along the Hinder Banks is in the ebb direction (SW); hence a zone of maximum shear can be roughly defined between both sandbank groups. In some of the swales of the Flemish Bank region, the maximum currents are also SW oriented. High currents of up to 1.6 m/s are modelled at the Westerschelde estuary (throat) and are SE-NW directed. The zone of high current velocities extends north of the Paardenmarkt shoal with values of 1 - 1.2 m/s and are roughly E-W oriented. Still, MUMM measured spring current velocities of up to 1.9 m/s in this region. High currents of up to 1.4 m/s are also found to the north of the BCS, towards the main channel of the Southern Bight of the North Sea.

Sediment transport modelling

Sediment transport modelling is a much more complex issue especially when the action of currents and waves is taken into account and the mode of transport, being bedload or suspended load. Suspended load transport may be the predominant mode of transport for finer grains (< 200 μm), while bedload transport is predominant for the coarser fraction.

Following the approach of SOULSBY (1997a), VAN LANCKER (1999) calculated the sediment transport in the western near coastal area on the basis of current meter data of Waterways Coast Division. Given the nature of the seabed and the strength of the flow, most of the sediment is carried in suspension whilst only a small fraction is transported as bedload. Grains up to 210 μm are easily transported throughout the area, whilst grains coarser than 250 μm can only be transported in swales with higher current velocities. The fact that the current ellipses are highly rectilinear (see figures of current ellipses) and that the currents are relatively strong in some of the near coastal swales means that a considerable amount of sediment can be advected along the swales and can act as a source of material for the sandbanks.

On the BCS most of the modelling work is concentrated on suspended transport mainly in the framework of the development of more efficient strategies regarding the dumping of dredged material. Sediment transport models applied to the BCS date back to 1975 (NIHOUL (1975); NIHOUL and ADAM (1975)). MUMM has developed different models of the BCS to simulate the suspended sediment transport under influence of tidal current velocity and waves (Stokes drift). The MU-STM model is a 2D sediment transport model, which solves the equation using a Lagrangian method (DE KOK (1994)). The erosion and sedimentation is modelled following Ariathurai-Partheniades (ARIATHURAI (1974)) and KRONE (1962). The model can take into account different sediment fractions, for every fraction the advection and diffusion of the matter in suspension is calculated. Description of the model and applications on BCS can be found in VAN DEN EYNDE (1995); VAN DEN EYNDE (1997); VAN DEN EYNDE (1998); VAN DEN EYNDE (1999a) and FETTWEIS and VAN DEN EYNDE (2000a; FETTWEIS and VAN DEN EYNDE (2000b; FETTWEIS and VAN DEN EYNDE (2001a; FETTWEIS and VAN DEN EYNDE (2001b). In Figure 8, a map of the bed composition is presented, which is used as initial condition. In Figure 9 and 10 some model results are shown.

The main conclusions of these studies are the following:

- The processes responsible for the high turbidity formation are the currents and the import of SPM through the Strait of Dover. Due to mainly the decreasing magnitude of residual transport and the shallowness of the area, the SPM is concentrated in the Belgian-Dutch coastal waters and is forming a turbidity maximum in front of Zeebrugge. The occurrence of a high turbidity zone can best be compared to a kind of sediment congestion; it is an open sediment system.

- The erosion of tertiary clay, Holocene mud and peat layers is partly responsible for the increase of the SPM concentration in the considered area. Still, tthe Strait of Dover is thought to be the major source.

- Fine-grained sediments are continuously deposited and re-suspended showing variations during tidal cycles, neap-spring cycles and during changing meteorological conditions. Deposition, re-suspension and transport of mud during a tidal cycle are basic processes and are responsible for the magnitude of the SPM concentration in the turbidity maximum area.

- The difference in magnitude between spring and neap tidal currents is partly responsible for the fact that the mud deposits are permanent. Especially, during neap tide, the mud has a higher probability to build up a structure, to consolidate and to increase its erosion resistance. More mud is thus found on the bottom and the SPM concentration is relatively low. During spring tide the opposite happens and part of these deposits are again re-suspended.

- The natural input of suspended sediments is higher - but of the same order of magnitude - than the quantities involved in the dumping of dredged material. This shows that an important part of the overall mud will be involved in the dredging/dumping cycle. If dumping places are situated in the turbidity maximum area the effect of dumping is small. If they are situated outside those zones, the NE directed coastal transport of SPM would decrease while further offshore the SPM transport will increase. If the dredged material is dumped in a deeper area, the increase in concentration is less than the decrease of concentration in the coastal area.

Towards bed load sediment transport modelling, ADAM et al. (1981) and DJENIDI and RONDAY (1984) used the erosion energy and the bottom friction to simulate the sediment transport in the Belgian coastal zone under the influence of tidal currents. DJENIDI and RONDAY (1992) modelled the sediment transport model (formula of Burgers) of the Belgian coastal area with a coupling towards the hydrodynamic model and taking into account morphological changes due to tidal currents. VAN DEN EYNDE and OZER (1993) integrated the influence of tides and waves using the total sediment transport formula of Ackers & White.

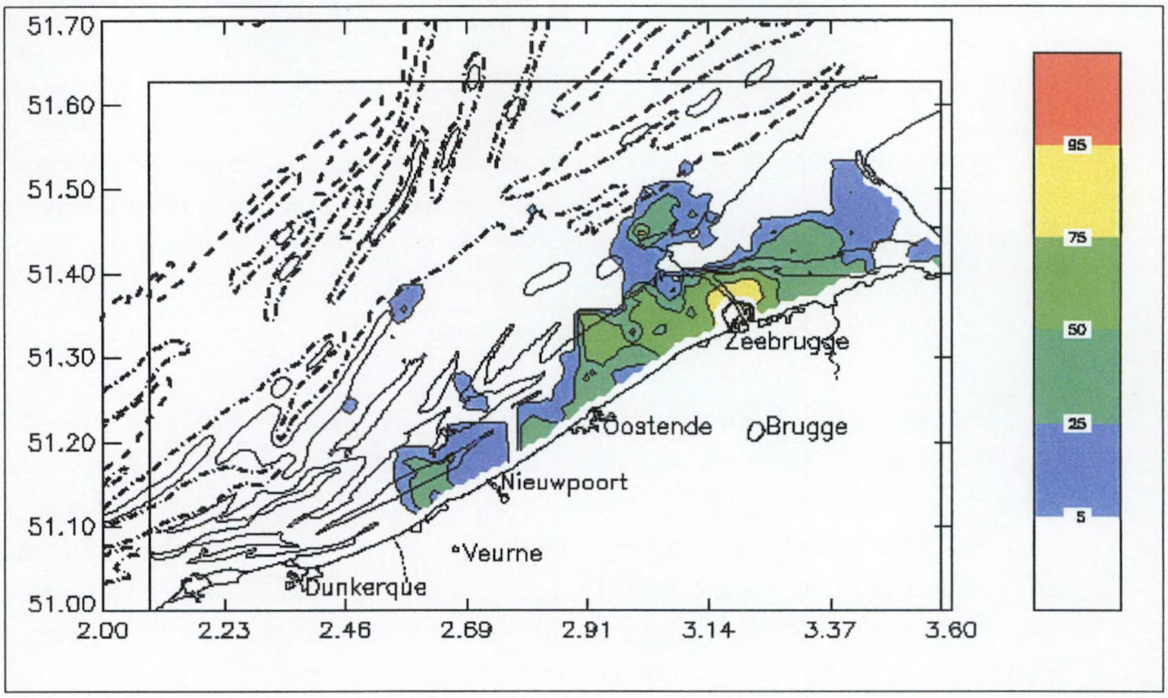

Figure 7. The map shows the mu-STM model boundaries, the 10, 20 and 30 m depth lines (MSL) and the mud (<63µm) content (% weight) of the surficial sediments. The mud content is calculated from a distance-weighted average of field data in a diameter of 3.75 km (i.e. 5 times the grid distance) and is used as input for the numerical model.

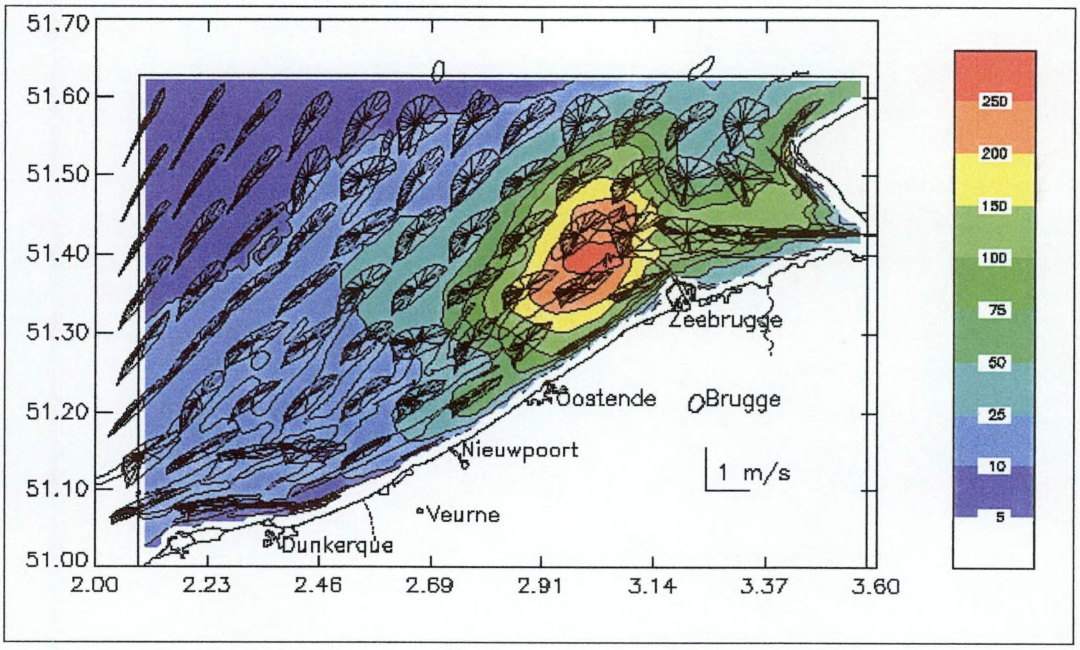

Figure 8 Tide-averaged SPM concentration (mg/l) according to a numerical model simulation (mu-STM) where the SPM concentration boundary condition is based on measurement data and where initially mud is present in the parent bed. Spring tide and current ellipses.

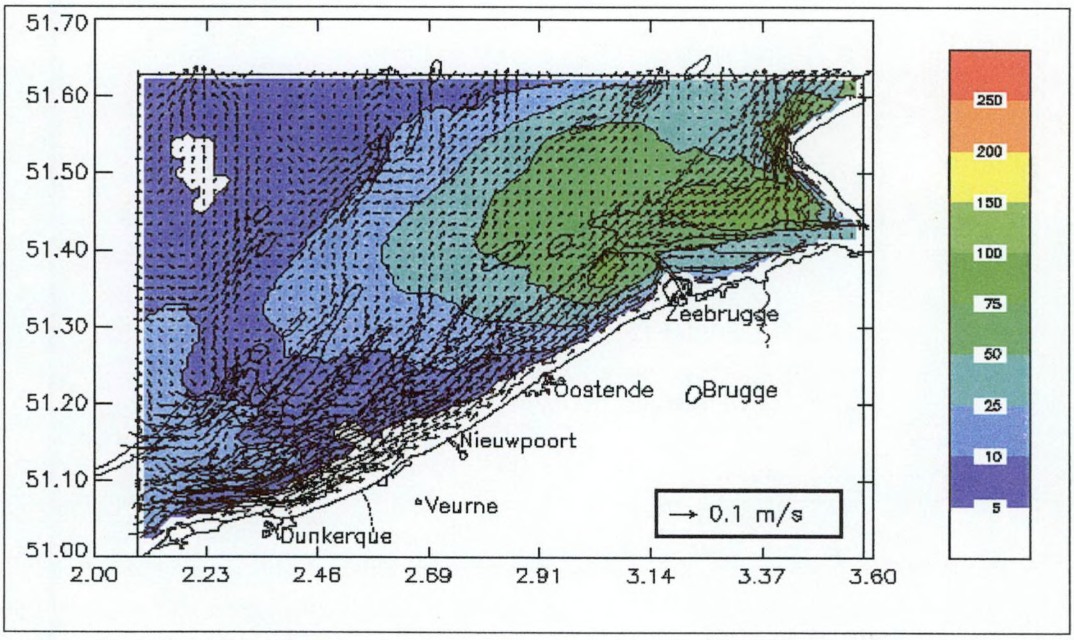

Figure 9. Tide-averaged SPM concentration (mg/l) according to a numerical model simulation (mu-STM) where the SPM concentration boundary condition is based on measurement data and where initially mud is present in the parent bed. Neap tide and residual transport vectors.

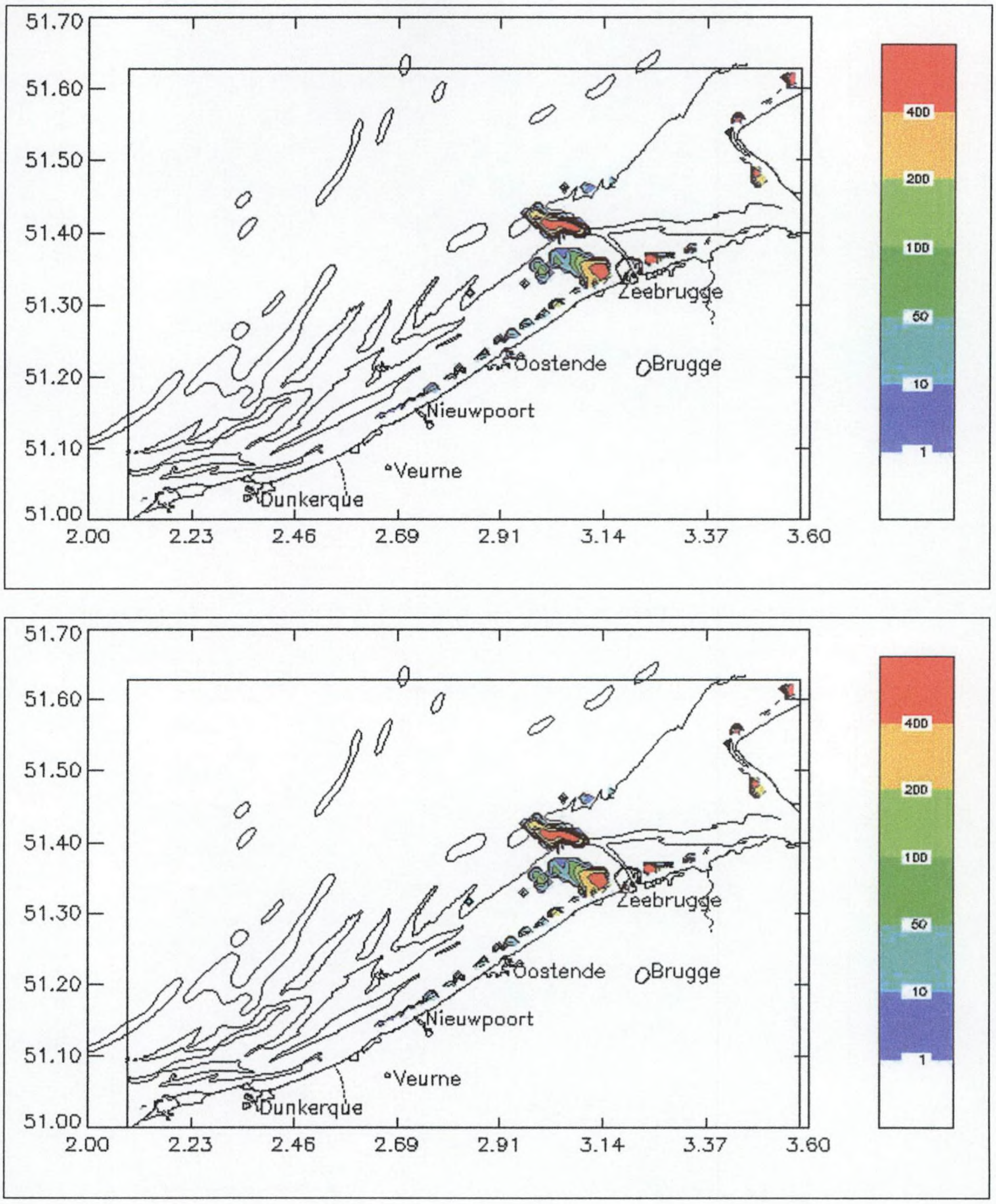

Figure 10. Mud deposition (in kg/m²) in the active layers according to a model simulation (mu-STM) where the SPM concentration boundary condition is based on measurement data and where initially mud is present in the parent bed. (a) spring tide and (b) neap tide. Assuming a bulk density of the mud of 1300 kg/m³, 100 kg/m² corresponds to a mud layer of $\pm$8 cm.

In the framework of this project, VAN DEN EYNDE (2001) developed a 2D sediment transport model (total load). The model (mu-SEDIM) is based on a local total load formula in each grid point. The bottom stress is calculated under the currents and waves and accounting for the roughness in the grid point, using a 2D hydrodynamic and a 2nd generation wave model. The total roughness is calculated from the median grain-size, from the calculated ripple height and steepness and the calculated bottom load. A total load sediment transport formula (Ackers and White) is used to calculate the sediment transport vectors. The simulations are executed for the year 1999. Figure 11 shows the calculated transport vectors.

The results show a sediment transport on the sandbanks in a clockwise direction: to the northeast on the W flank of the banks and southwest directed on the E flank of the bank. In the coastal zone (20 km) the transport direction is towards the northeast. In the Scheur the direction is towards the west. In open sea (north of the sandbanks) the sediment transport direction is towards the southwest.

It should be mentioned that most of the sediment transport models have been set-up by foreign institutions and subsequently most of them are applied outside the BCS (see also VAN DEN EYNDE (1994)).

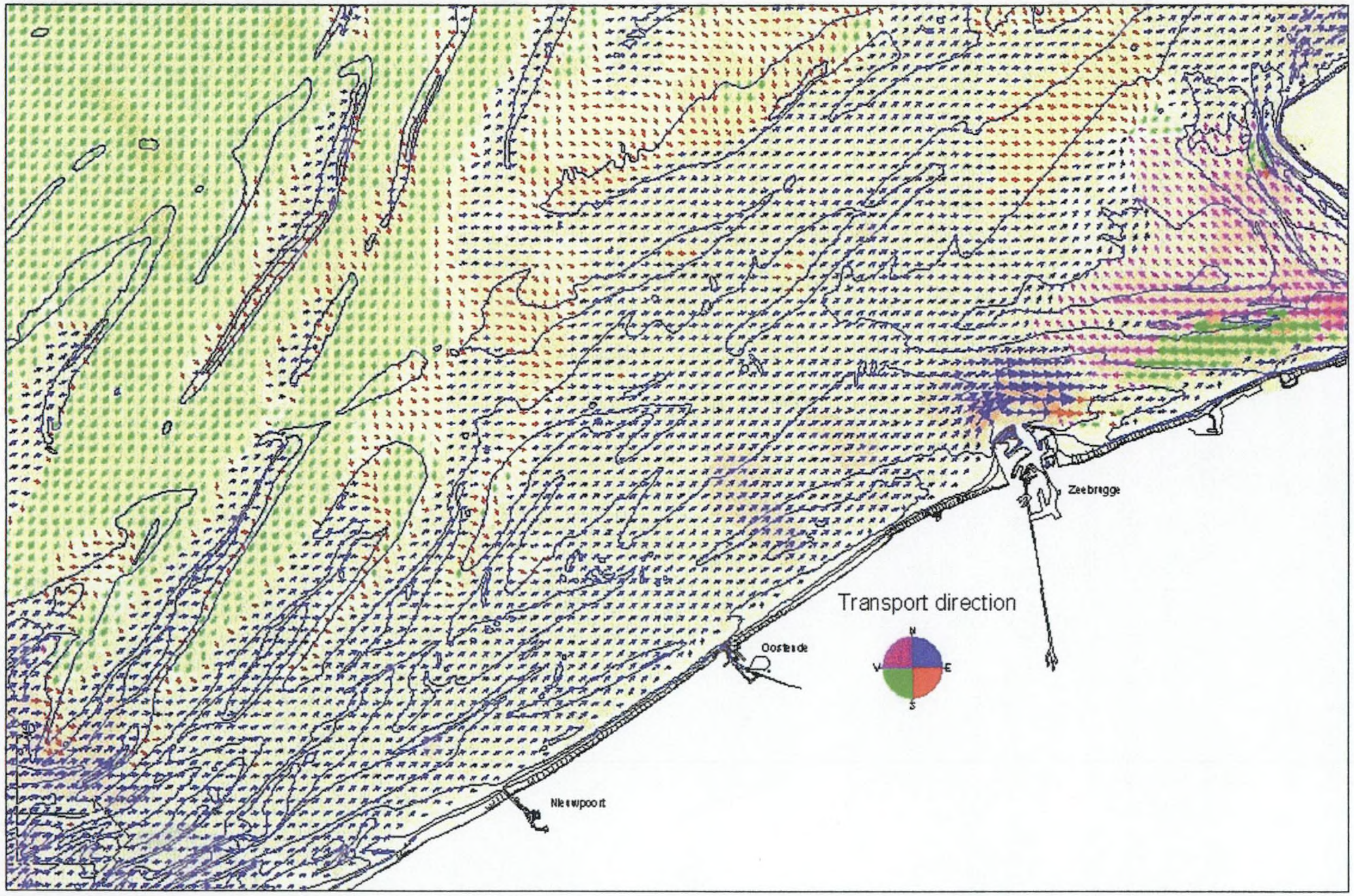

Figure 11. Transport vectors obtained from a 2D sediment transport model (total load). The coloured vectors group the direction of the transport vectors per quadrant

3.2. Overview of sediment transport studies related to the Belgian continental shelf

3.2.1. Inventory of the qualitative studies and their research methods

The inventory included the analysis of the numerous publications and reports related to the residual sediment transport on the BCS. In Annex 1, each of these studies has been summarised in an abstract of one page. The abstract includes details on (i) the method (such as sampling interval, type of instrument) used for the deduction of the residual transport directions, (ii) the principal results (always in relation to the sediment dynamic point of view) and (iii) the directions of residual transport that could be derived. Although the main emphasis of the present study was on the transport of sandy sediments, it became obvious that results concerning the suspension fluxes of cohesive sediments were as well a valuable contribution to the overall picture of the sediment movements on the BCS and therefore they were also included.

The inventory does not aim particularly on individual publications, but focuses more on the project level. Different publications highlighting slightly different sediment dynamic aspects obtained in the framework of a single project were therefore often collected in a single summary. The original idea to classify all studies in function of the spatial scale in which the experiment took place could not be maintained, at least at the level of the inventory as the different techniques could reveal information on different scales. Finally, it was decided to classify the studies according to the principal technique that was applied. The spatial and time scale of each technique is discussed and defined in Paragraph 3.4.
A database was also compiled in the form of an Endnote Library file enabling an efficient search throughout the multidisciplinary studies.

3.2.2. Inventory of the quantitative studies and their research methods

A similar approach as described above was used for the studies having results on quantities of transported sediment. A synthesis of each research project was produced and can be found in Annex 1. Again a classification of this type of studies was based on the used technique. No distinction between qualitative and quantitative studies was made in Annex 1 as different studies often produced both quantitative and qualitative results.

3.2.3. Inventory of the modelling studies

The same approach was used as described above.

3.3. Critical analysis of the data and the methods used

3.3.1. Residual transport directions based on the asymmetry of bedforms

Introduction

The asymmetry of bedforms has been one of the first techniques to be used for the determination of the residual direction of sand transport. This is based on the concept that the steep side of an asymmetric bedform indicates the direction of advance of the feature and the strike of their crest line is generally perpendicular to the flow. In a tidal regime the direction of sediment transport would be caused by the fact that during ebb (or flood) a slightly larger quantity of sand is transported than during flood (or ebb).
The following flow-transverse bedforms could theoretically be considered (from large- to small scale): (i) sandbanks, (ii) large to very large dunes ("sandwaves" as they were defined in most of the earlier papers), called hereafter large dunes, (iii) small to medium dunes (earlier mostly defined as "megaripples"), called hereafter small dunes and (iv) ripples (ASHLEY (1990)).

If bedforms are to be used as residual transport indicators they should fulfil following conditions: (i) their asymmetry should be induced by the present-day hydrodynamic processes, (ii) their steep slope should represent a depositional surface and (iii) their asymmetry should represent an equilibrium of a longer time scale than the daily tidal effect.

The smallest bedforms, ripples, can in this case not be used for residual transport studies as they change their asymmetry with each tide as proved by direct observation or from the analysis of ripple profiler data (BELL and THORNE (2001)).

Most of the sandbanks off the Belgian coast have an asymmetric profile. The Coastal Banks have a landwards-directed steep slope (DE MAEYER and WARTEL (1988); VAN LANCKER 1999), the Flemish Banks' steep slope corresponds to the western flank (DE MOOR (1985)), the Zeeland Ridges have again a landwards-directed steep slope (VAN LANCKER (1993)) and the Hinder Banks mostly witness a steeper eastern flank (DELEU 2001). In the past these directions have been used to define the large scale sediment transport pattern for the Southern Bight of the North Sea (KENYON et al. (1981)), however many arguments exist to prove that in fact the steep slope can be considered as an erosional surface and is merely created by the stronger tidal current along that flank (HOUTHUYS (1989), VAN LANCKER 1999, DELEU (2001)). This means that the asymmetry of the sandbanks off the Belgian coast cannot be used as net sediment transport indicators.

Large dunes have been extensively used in marine environments to deduce the residual sediment directions. STRIDE (1963; STRIDE (1965) used sandwaves to map the residual transport paths around the southern half of Great Britain. Two main directions on the Belgian shelf were distinguished: a northeastward direction in a coastal section and a southwestward direction more offshore. However TERWINDT (1971) in a study on sandwaves in the Southern Bight declared "sandwaves cannot be used as an indication for sand transport directions" as there was no proof that the asymmetry of the large dunes was created by present-day hydraulic conditions.

McCAVE and LANGHORNE (1982) however suggested that the small dunes, very often superimposed on the large dunes, were better indicators of residual sediment movement. SWIFT and FIELD (1981) found as well that their flow measurements were in conformity with the pattern of the small dunes.

It is worth mentioning that non flow-transverse bedforms, such as sand ribbons, have also been used to map residual transport directions (STRIDE (1963); BECK et al. (1991)). These bedforms tend to develop on a substratum made up of gravel, stones or shells. Although, they have been recently reported by DELEU (2001) and DEGRAER et al. (2001), information on these features off the Belgian coast is scarce and therefore they will not be considered in the present report.

A compilation of published research showed that both large and small dunes have been used as indicators of net transport on the Belgian shelf. In all these studies directions of residual transport were defined, however the validity through time remained uncertain and the question remains if the directions correspond to a long-term evolution (scale of many years) or if they merely represent much shorter processes (scale of days-weeks).
If the time-scale of the residual transport directions has to be unravelled, it is necessary to analyse thoroughly the evolution of the bedforms. Therefore a synthesis of the characteristics of small and large dunes, with emphasis on their asymmetry was made, based on the research carried out on the Belgian shelf.

<u>Large dunes</u>

The large dunes were probably the first features to be used for sediment transport studies as they are large enough to be easily mapped with the help of single beam echosounding equipment.

Some of the earlier studies that used large dunes as transport indicators were based on a reduced number of cross-sections of the seabed. The study of TERWINDT (1971) was based on three sounded tracks and an analysis on large dunes carried out by STRIDE (1970) relied on a single echosounding track sailed along the Dutch coast. However, if bedforms have to be used as sediment transport indicators, it is highly advisable (i) to map their extension and geometric characteristics along their entire crest line (by using for example a side-scan sonar or a multibeam echosounder) and (ii) to survey the area of research several times in order to check the influence of shorter-term processes on the results.

Earlier studies on large dunes occurring on sandbanks (VLAEMINCK et al. (1989): analysis on the Goote Bank, Buiten Ratel and Oost Dyck; DE MOOR (1985): analysis on the Kwinte Bank; CASTON (1972): analysis of the Oost Dyck), based on a number of echosounding tracks crossing the bank, formulated the conclusion that large dunes on both bank flanks had their steep slope dipping towards the bank's axis hence indicating a convergence of sand streams towards the bank's crest. The large dunes would in this case be flood-asymmetric (steep slope dipping towards the northeast) on the western flank and ebb-asymmetric (steep slope dipping towards the southwest) on the eastern flank of the bank. Although this conclusion may be generally correct, it is impossible to know from a single recording if the dunes are always identically shaped.

From full-coverage side-scan sonar observations, the asymmetry of the large dunes seemed to be much more complex. Initially, parts of sandbanks were studied using this approach, such as the northern part of the Kwinte Bank (LANCKNEUS et al. (1992), VANWESENBEECK (1994)) and the central part of the Goote Bank (VAN LANCKER (1993)). The latter showed a dominance of ebb-asymmetric large dunes along the whole bank section. In the framework of the MASTI Resecused project, the asymmetry of the large dunes was examined along the entire Middelkerke Bank using the results of side-scan sonar imagery (LANCKNEUS and DE MOOR (1994)). Figure 12 represents the crest lines of the large dunes on the Middelkerke Bank (survey carried out in May 1990).

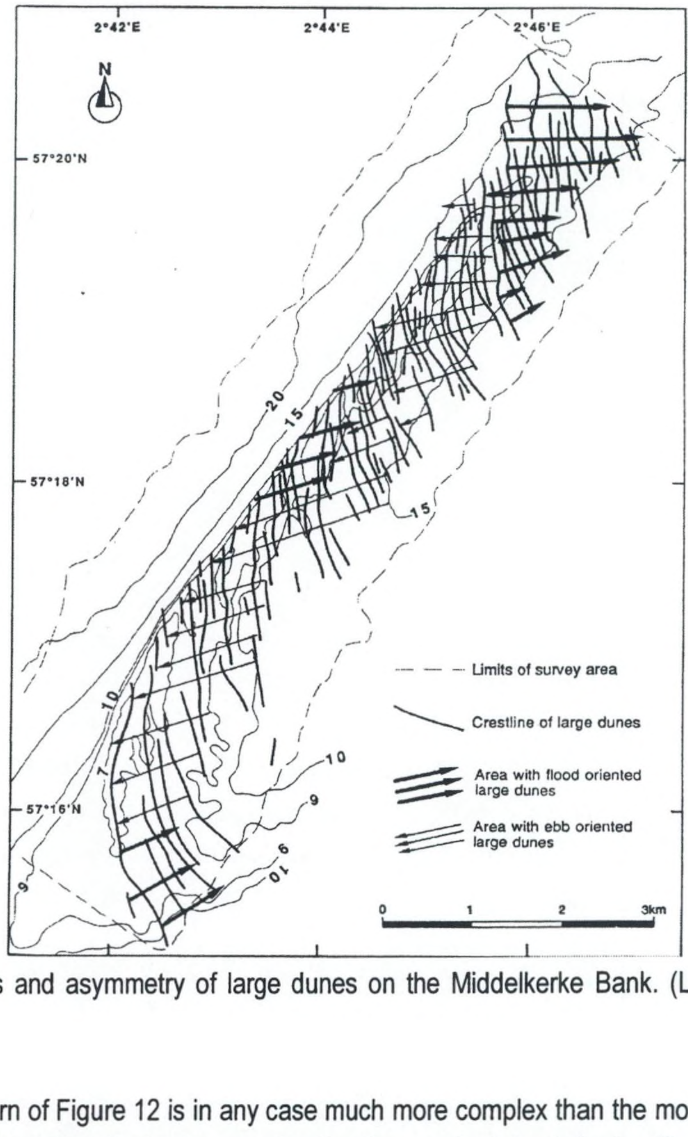

Figure 12. Crest lines and asymmetry of large dunes on the Middelkerke Bank. (LANCKNEUS and DE MOOR (1994)).

The asymmetry pattern of Figure 12 is in any case much more complex than the model in which the large dunes have their steep slopes dipping in opposite directions on both bank flanks. Figure 12 shows that the

large dunes of both bank ends have their steep slope dipping towards the northeast. The central area of the bank is characterised by large dunes with steep slopes facing towards the crest of the bank on the two bank flanks. Between the central area and the two bank ends, large dunes with a steep slope dipping towards the southwest are found.
The results of additional surveys on the same bank add even more complexity. Time-series of bathymetric and side-scan sonar recordings pointed out that situations exist in which nearly all large dunes on the bank can be (i) ebb-asymmetric, (ii) flood-asymmetric or (iii) different combinations of ebb-asymmetry and flood-asymmetry.
Lack of time-series of measurements may explain the fact that few authors comment on a reversal of the asymmetry of large dunes. Figure 13 presents a number of bathymetric recordings across the Middelkerke Bank along the same reference line (LANCKNEUS and DE MOOR (1994)).

Several changes in asymmetry can clearly be observed. Furthermore the analysis showed that some large dunes reverse their asymmetry within a single month and that individual dunes can disappear completely as observed on 23/03/1990. The bank however always seems to recover from such abrupt changes, the restored cross-section in this case being characterised by four large dunes.

There is little doubt that the large dunes are being shaped by the tidal currents. In this case flood and ebb currents would be responsible for the asymmetry of respectively flood-asymmetric and ebb-asymmetric large dunes. The observed switches in asymmetry must then be caused by an additional factor that enhances the flood or the ebb current.

Other authors faced the same question. BERNE (1991) was not able to explain the asymmetry of some large dunes by tidal dynamics alone and thus invoked other processes. LANGHORNE (1982) showed that swell and winds were able to modify the duration and intensity of tidal currents in Start Bay (UK). Such modifications can thus increase or decrease the strength of either flood or ebb currents and could thereby induce a particular asymmetry in the large dunes. This was previously suggested by STRIDE (1963) who confirmed that the strength of a tidal current could temporarily be enhanced by a wind-induced current causing unusually large quantities of sediment to be moved.

The effect of hydro-meteorological conditions on the asymmetry of large dunes was investigated on the Middelkerke Bank (LANCKNEUS and DE MOOR (1994)). The wave and wind characteristics in the vicinity of the survey area during a period of 10 days prior to the survey date were analysed and correlated with the results of the residual transport directions. Figure 14 displays both hydro-meteorological parameters and asymmetry of the large dunes.

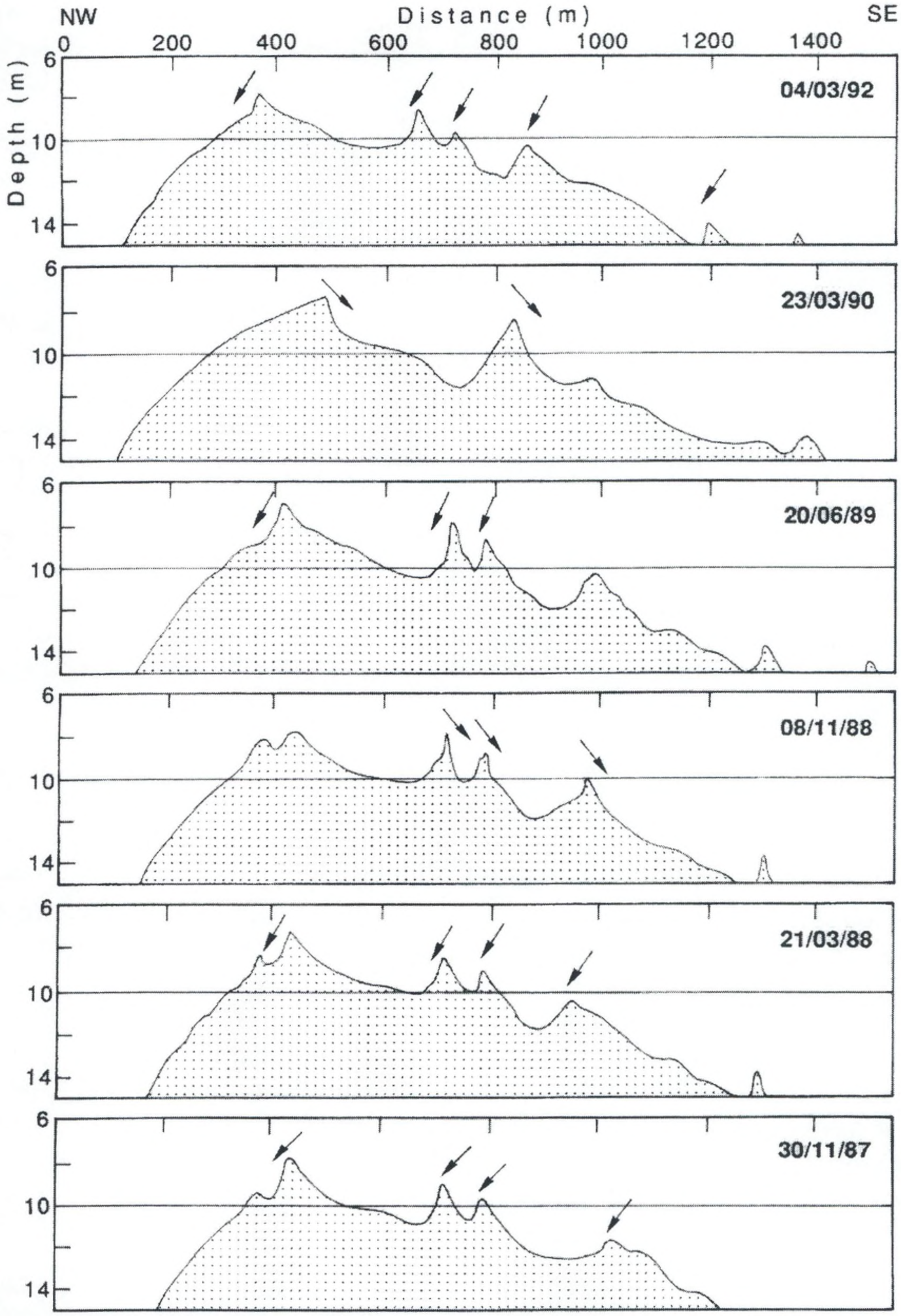

Figure 13. Bathymetric recordings along a single reference line obtained in the course of repeated surveys between 1987 and 1992 (LANCKNEUS and DE MOOR (1994)).

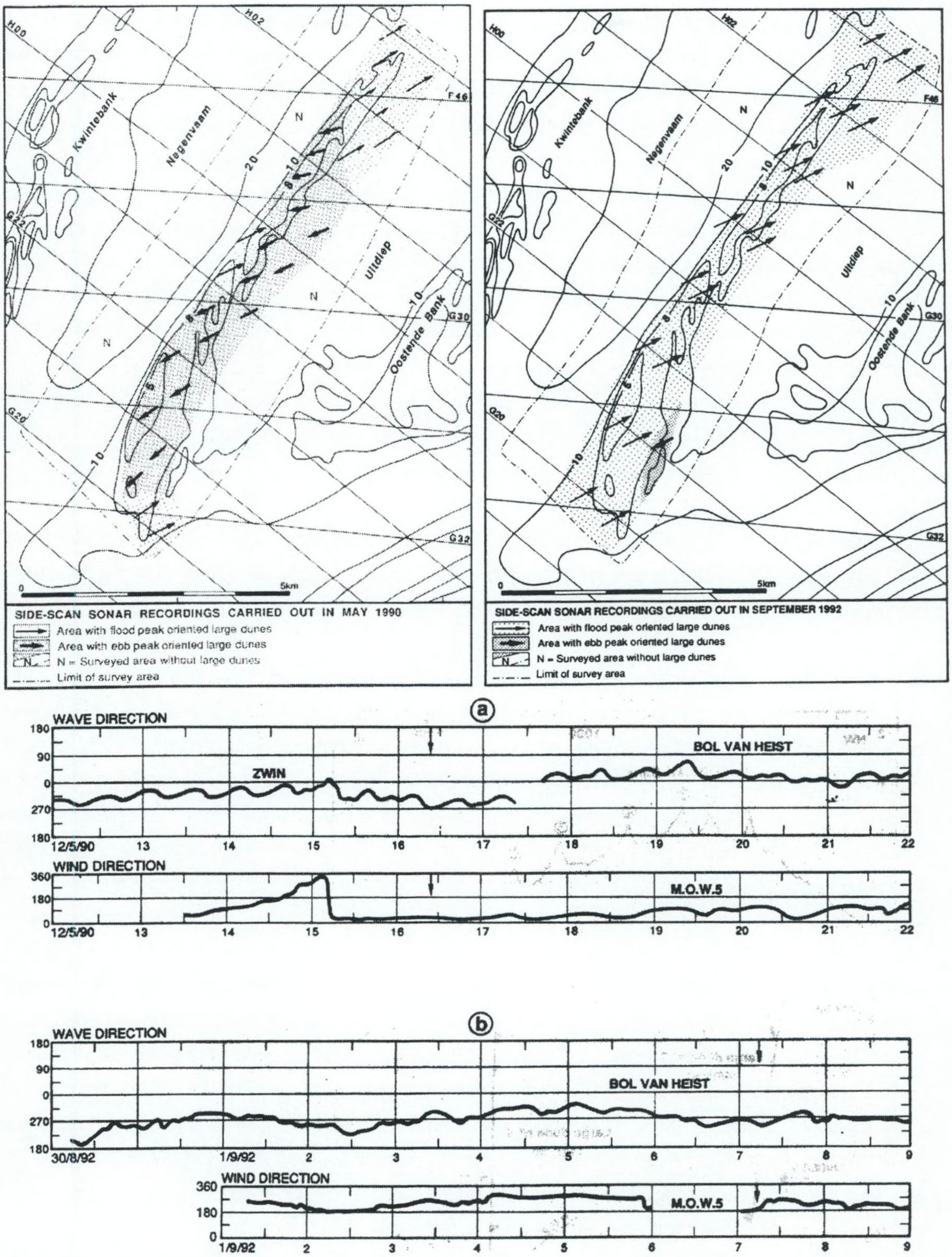

Figure 14. Asymmetry of large dunes and wave and wind direction of the period prior to the side-scan sonar recordings (LANCKNEUS and DE MOOR (1994)). Wave directions recorded with directional wave buoys and wind direction data from the measuring pile MOW5 for the periods 12-22 May 1990 (a) and 30 August – 9 September 1992 (b). The arrows indicate the days of the bathymetric surveys.

In the first period (second half of May 1990) north-northeastern winds and a northern swell dominated which seemed to have amplified the ebb current, causing the large dunes to become dominantly ebb-asymmetric. In the second period (first half of September 1992) winds and swell from the southwest were dominant for 10 days and probably induced the flood-asymmetry of nearly all large dunes. One particular storm and swell coming for example from the southwest will however not affect the asymmetry of all features simultaneously. The moment a particular large dune will reverse its asymmetry will mainly depend on its size. A smaller large dune (height of 0.5 m) could reverse its asymmetry after a few days while a larger feature (height 2 to 3 m) will need the dominant wind and swell to last for a longer time in order to adapt to the new flow regime. The result of a storm of a few days will in this case cause the asymmetry pattern of the large dunes to be quite complex and hybrid. This phenomenon could explain the existence of different combinations of ebb- and flood-asymmetric large dunes as the one observed in Figure 12. If calm weather is prevailing for a long period, the asymmetry pattern will evolve to a pure tidal current situation in which flood-asymmetric bedforms will dominate on the western bank flanks and ebb-asymmetric structures will be dominating on the eastern bank flanks.

The asymmetry of the largest of the large dunes, such as the ones occurring on the northern Kwinte Bank with heights up to 8 m, can be considered as permanent as no reversal was observed in the course of 40 surveys between 1984 and 1992.

A sediment- and morphodynamical investigation in relation to hydro-meteorological conditions was carried out in the western near coastal area (VAN LANCKER (1999); VAN LANCKER and JACOBS (2000)). Fields of large dunes were monitored in the period 1995-1999 and included geo-acoustical techniques and sampling. O'SULLIVAN (1997) worked on the dunes of the southern part of the Middelkerke Bank whilst DELGADO BLANCO (1998) focussed on the Ravelingen dune field (offshore Oostende, E of the Oostende Bank). Emphasis was put on the dynamics of the Baland Bank (small sandbank in the interaction zone of the Stroombank and the Nieuwpoort Bank) dune field (heights up to 2 m), as these are located in a convergence area of a flood- and ebb-dominated swale. The dune fields were also volumetrically followed up to a time-series of 12 observations. Generally, the occurrence of the larger bedforms showed a remarkable stability although storms of up to 12 Bf had taken place. The asymmetry of the Baland Bank dune field was uniform NE directed (regional sediment transport direction), however their shape indicates as well the effect of the ebb tidal current. Survey results of one campaign showed a complete reversal and displacement of all dunes in a SW direction that could be linked to the effect of an 8 days period of moderate, but persistent NE winds. In the interaction zone of the Flemish Banks, the bedforms tend to be NE or flood directed. However, the dunes occurring in the vicinity of the ebb shaped swales are mostly ebb-dominated with a strike that is generally bent in the direction of the ebb tidal current. The whole is likely indicative of a bedload convergence.

The dataset of the Baland Bank dune field allowed to quantitatively relate the volume of sediments to the ruling hydro-meteorological conditions (VAN LANCKER (in prep.)). Generally, the highest volumes were found after stormy periods as its sediment input is directly related to Westdiep swale characterised by a high sediment transport capacity. Moreover, it was deduced that northeastern conditions are associated with the lowest sediment budgets, whilst strong winds blowing from the southwest are associated with a sediment input (Figure 15). From the temporal observations including bedform migration, it seemed that the consistency and hence duration of the prevailing hydro-meteorological conditions was more important than the strength. During the 4-years observation period, it also seemed that the area recovered fairly quickly from stormy periods as was expected from sediment transport calculations.

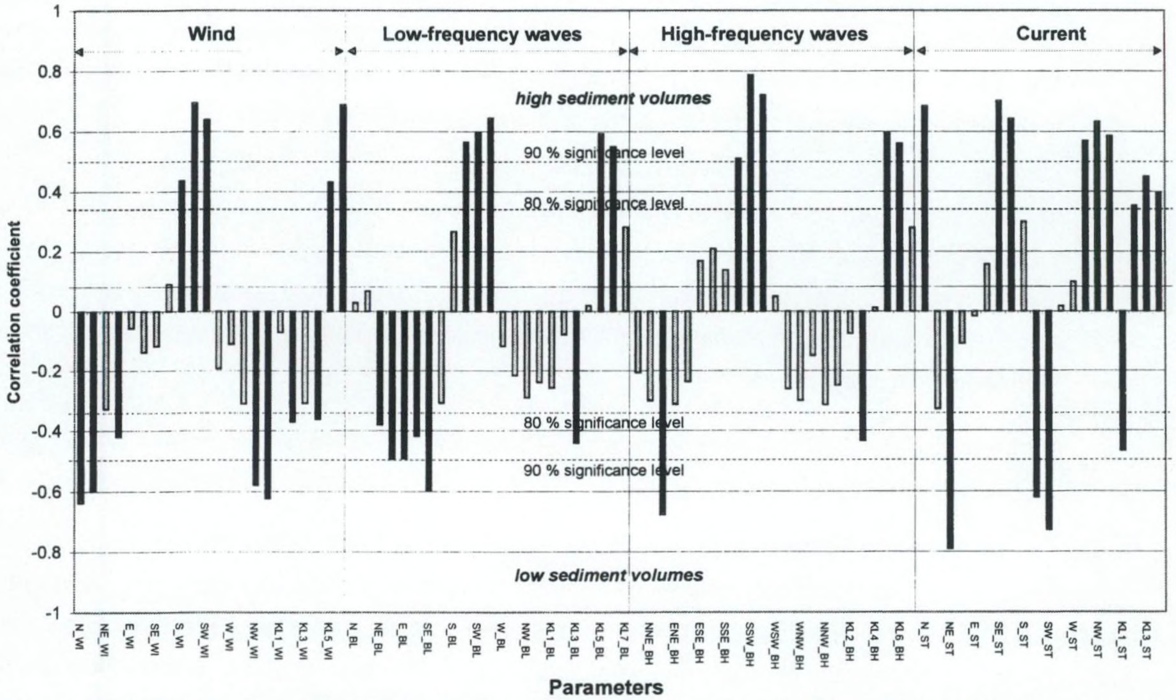

Figure 15. Correlation coefficients of the link between sediment volumes and the directionality and strength of the sand transporting agents wind, waves and current (VAN LANCKER in prep.). Note the strong positive correlation of the sediment volumes with strong SW winds (> 90 % significance for SW_WI and KL5_WI) and high waves from a SW direction (> 90 % significance for SW_BL and KL7_BL). Also, note the strong negative correlation with N to NE winds (> 90 % significance for N-NE_WI).

In the framework of the OSTC HABITAT project (DEGRAER et al. 2001), very-high resolution geo-acoustical methods were applied to temporally study the bedforms of the Westdiep-Trapegeer-Potje-Broers Bank near coastal system. One large dune of more than 2 m was observed in the Westdiep swale that was clearly NE directed. Remarkably, large dunes of up to 2 m occurred in the shallowest areas and seemed to be merely ebb-dominated as well in shape as in asymmetry. This is likely due to the higher resuspension potential of the ebb tidal current, which is of high importance in the shallowest areas (VAN LANCKER et al. 2000).

If we consider the studies on large dunes off the Belgian coast based on time-series of observations, it can be summarised that:

- nearly all large dunes can change their asymmetry and present an ebb-asymmetry or a flood-asymmetry.
- the height of all dunes can vary through time; the variations are in fact oscillations around a particular value. The height can be lowered by heavy weather (crest lines of large dunes on the Middelkerke Bank were lowered 1.2 m by a storm) (HOUTHUYS et al. (1994)); the sediments are likely temporally stored in the troughs of the bedforms (VAN LANCKER 1999);
- the migration rate of the large dunes is in most cases not significant. The large dunes are subject to oscillatory movements resulting in a minor net migration (LANCKNEUS and DE MOOR (1991), LANCKNEUS and DE MOOR (1994); VAN LANCKER 1999, VAN LANCKER (in prep.)).
- displacement of the large dunes can occur as well in the direction of the steep as of the stoss slope. This means that the asymmetry of a large dune does not always show the direction of short-term sediment transport.

Small dunes

Fields of small dunes can be found on the sandbanks (superimposed on the large dunes) as in the swales. Small dunes are in most cases too small to be deduced from echosounding recordings and have to be analysed on the basis of side-scan sonar mosaics of processed multibeam data. Let us examine in first place the extent, orientation and asymmetry of small dunes on one sandbank (Middelkerke Bank, LANCKNEUS and DE MOOR (1994)).

On Figure 16, it is clearly visible that the lee slope of the small dunes dips in opposite directions on either side of the bank. In the western swale and western section of the bank they dip to the northeast, whereas in the eastern swale and eastern section of the bank they dip towards the southwest. The division between the ebb- and flood-oriented small dune fields is sharp and a line can be drawn from the northeast to the southwest, more or less parallel to the axis of the bank.

As we have seen that hydro-meteorological conditions can affect the asymmetry of the large dunes, it seems obvious that wind and swell from a particular direction will as well be able to induce asymmetry changes for the small dunes and this even faster than in the case of the large dunes. Time-series of side-scan sonar recordings on the Flemish Banks and more specifically on the Kwinte Bank (LANCKNEUS and DE MOOR (1991)) showed that nearly all small dunes can be ebb- or flood-asymmetric in time.

Noteworthy is that time-series recordings on the Flemish Banks during a tidal cycle has shown that the small dunes did not change their asymmetry in relationship with the tidal current. DALRYMPLE (1984) reached a similar conclusion from his research in the Bay of Fundy. Much will of course depend on the size and the strength of the tidal current.

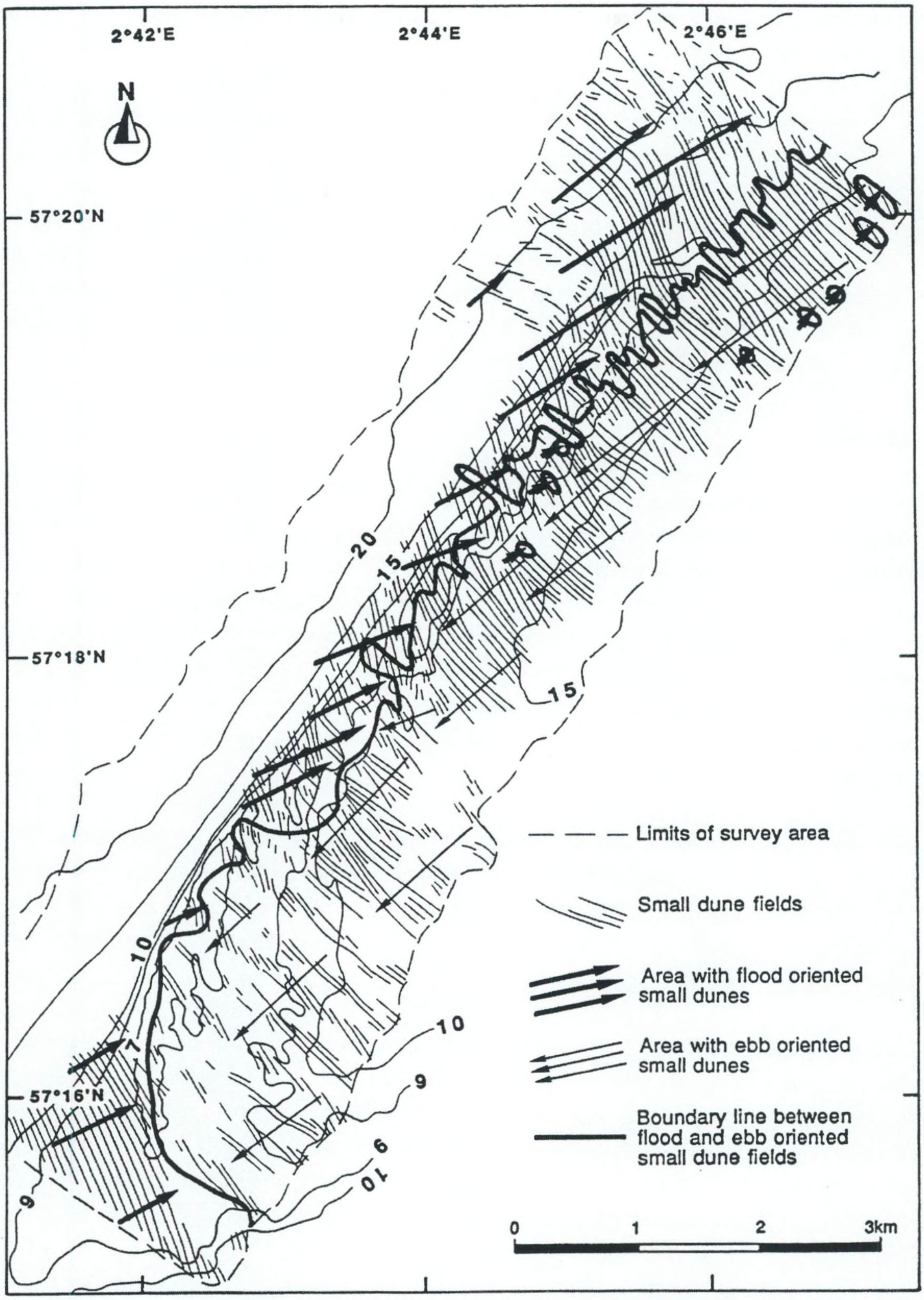

Figure 16. Residual transport directions based on small dunes (LANCKNEUS and DE MOOR (1991)).

On the basis of time-series of recordings of small dunes (LANCKNEUS and DE MOOR (1991)) presented the following sediment dynamic model for the Flemish Banks region:

- The banks receive sand from both adjacent swales. Residual flood currents from the southwest command the residual sand transport on the western flanks, while residual ebb currents from the northeast are responsible for the sand transport on the eastern flank. As a result sand is moving residually in each swale along two opposite directions. This causes a sand up piling on the bank summit. On the summit sand can travel residually in opposite directions along parallel ribbons. The width of these ribbons and the importance of this transport can vary significantly along the bank axis and through time. The residual transport of the sediment can be exclusively to the north, exclusively to the south or can be divided along two channels of similar importance. It is likely that a sediment dynamic model based on large dunes would give similar results.

Conclusions

Enough data is available to proof that both small and large dunes are active features shaped by the present-day hydrodynamic environment. The short tidal cycle does not allow sufficient time for the entire volume of sediment stored in the small and large dunes to be entirely reworked. Instead the opposing currents continuously modify the bedform profile and the overall shape represents a state of quasi-equilibrium to the relative strength of the opposing flows. The asymmetry is in the first place defined by the dominant tidal current. This means that on the Flemish and Hinder Banks, the residual flood current shapes the bedforms on the western bank flank and the eastern part of the swale while a residual ebb current is responsible or the ebb-asymmetry of the bedforms on the eastern bank flank and the western part of the swale.

Hydro-meteorological conditions are able to alter the asymmetry of all bedforms (with the exception of the largest). The speed of this adaptation to the net transport direction is function of the size of the bedform: small dunes will change their asymmetry faster than large dunes. Once the storm is over, the bedforms will return to their original tidal induced asymmetry, but again the speed of this change will depend on their size.

A model of the residual sediment transport, based on large dunes would be very similar to a model based on small dunes. Small dunes have the advantage that (i) they have a broader distribution (they are found not only on the sandbanks as the large dunes, but as well in the swales where large dunes are generally rarer) and (ii) they adapt their shape faster to new current conditions (as their height is more or less uniform, they change more or less all simultaneously to the new hydrodynamic environment making them less subject to hybrid situations like the ones encountered with the large dunes).

Furthermore sediment transport takes basically place by migration of the small dunes that are superimposed on the large dunes, which act in this case as transport platforms.
The residual transport directions on the Belgian shelf based on the asymmetry of bedforms are given on the synthesis map. The residual directions are a compilation of different recordings. The impact of

punctual processes (such as storms) was filtered out. Therefore they correspond to a time-scale of the order of years. The transport directions on the Flemish Banks were deduced from the small dunes. The directions on the Hinder Banks were derived from the large dunes (no information on small dunes available). The arrows of residual sediment transport on the Goote Bank were derived from the large dunes too. Large dunes were used in this case because they were very large (height > 5 m) and located in relatively deep water (20 m) and on a smooth topography.

The directions on the map refer in the first place to the residual sediment dynamics active on the scale of the individual banks and swales. It is however more difficult to derive the residual transport direction from one bank in the system to the next one. A possibility would be to deduce the net cross-bank transport direction from the dominant group of large dunes (ebb- versus flood-asymmetric bedforms). DELEU (2001) studied the characteristics of the large dunes in the Hinder Bank area (based on survey work performed in 2000) and calculated that 42 % of the large dunes were ebb-asymmetric, 26 % flood-asymmetric and 32 % symmetric. The larger amount of ebb-asymmetric dunes could be used as an argument to state that in the Hinder Bank area the residual cross-bank transport might take place in a westward direction. HOUBOLT (1968) performed a similar calculation (based on recordings carried out in 1963 and 1964) and found as well that south-pointing asymmetric large dunes predominated over north pointing ones, which led him to believe that the net transport over the ridges was towards the southwest.

3.3.2. Residual transport directions based on tracer experiments

Introduction

A number of tracer experiments have been carried out on the Belgian shelf to deduce residual transport directions. The majority of these experiments were performed in the framework of the construction of the extension of the harbour of Zeebrugge (1978-1988) and were therefore carried out in the vicinity of Zeebrugge.

A tracer consists of marked particles that are injected in the environment at a certain injection point. These particles must duplicate the behaviour pattern of local sediments and should have a similar grain-size distribution and density as the original sediment. After a certain time interval a plume of marked sediments is formed on the sea floor that can be detected and measured. The plume can be described as a net of lines of equal concentration. By monitoring the evolution of the plume through time it becomes possible to map the paths followed by the sediments and to deduce the residual transport directions. It is also possible to derive quantitative parameters as the transport velocity and quantity (BASTIN et al. (1983)).

The three main techniques that have been applied on the Belgian shelf and on beaches are the radioactive, the fluorescent and the magnetic tracer experiments. They can provide sediment transport patterns on a local or regional scale.

Radioactive tracers

- Radioactive tracers have mainly been used for suspension transport of fine-grained sediments (mud) on the BCS. Although, their use is nowadays no longer possible because of health and safety concerns, different radio-isotopes have been used in previous experiments. Care was taken regarding the lifetime of the radioactive source as to exceed the duration of the experiment, but not by so much as to avoid major contamination of the area. For all bed-load experiments, the isotope Iridium 192 was used. For producing the tracer particles, Iridium was melted in a special glass, milled to the desired grain-size and then activated in a reactor. The detection unit consisted of a gamma scintillation counter fixed to a sledge and pulled over the seabed. In the case of the suspension-load experiments, the natural silty sediment was marked with the radio-isotope Hf 175 or Tb 160. The tracers were pumped to a sledge, which was pulled over the seabed, and injected in the water. Water samples were taken after which the isotope content in the fine fraction was determined by spectrometry.

Fluorescent tracers

- Sand with a similar grain-size distribution than the natural sediment in which the experiment takes place, is dyed with fluorescent paint. The marking substance should be strongly fluorescent, easily distinguishable from the colour of naturally fluorescent minerals of the environment and stable for a reasonable length of time. The detection of the tracer can take place in-situ (photography with U.V. film), which is often the case on beaches or can be carried out by sampling and coring followed by detailed analysis in the laboratory (so far standard procedure for offshore experiments). The injections are carried out with several tens to several hundreds kg of fluorescent sand.

Magnetic tracers

- Magnetically enhanced sands can as well provide rapid field data on the direction of residual sediment movement. This technique depends on converting iron coatings on silica grains to magnetite/maghaemite. Suitable sands are available from quarries in red glacial outwash sands from Triassic rocks in North Wales and from Cretaceous Greensand quarries in Bedfordshire. The magnetic enhancement process involves heating the sand at high temperatures (700 °C) for two hours in a reducing atmosphere followed by rapid cooling in air. The material is then sieved and different percentage weights of each grain-size class are added in such a way to obtain the grain-size distribution of the sediment in which the experiment takes place.

Radioactive, fluorescent and magnetic tracers are all artificial substances with a particular characteristic that makes them traceable when mixed with the natural sediment. However it is as well possible to use natural elements, such as salinity or the superficial water temperature, to obtain similar results. The results of the tracer experiments are summarised hereafter. A first distinction is made between bed-load tracing and suspension-load tracing experiments.

Bed-load tracers

Radioactive, fluorescent and magnetic tracers have been used to analyse the residual transport directions of the bedload. Bedload tracer experiments took mainly place around the Harbour of Zeebrugge; only one fluorescent tracer experiment was found that was carried out on a large tidal sandbank (the Middelkerke Bank). Table II. summarises the results of bedload tracer experiments. The following elements can be deduced:

- Eastwards of Zeebrugge, two directions of residual transport can be distinguished: an eastwards and a coastwards direction. The coastward direction is mainly the result of wave action in very shallow water coupled to stormy weather conditions. The experiment in the western Appelzak points to a clear northeast component. The three experiments on the beach show all a residual transport direction towards the Dutch border.
- North of Zeebrugge (Pas van het Zand), two experiments indicate a residual transport in the ebb direction. The remaining experiments in the flat area, north of Scheur (Wandelaar, Akkaert Bank, Sierra Ventana) show negligible residual bedload transport.
- A bedload tracer experiment carried out on the Westdyck (French shelf) indicates a residual bedload transport in a northeast direction towards the Flemish Banks.
- During a fluorescent tracer experiment on the Middelkerke Bank (WILLIAMS et al. (2000)), 500 kg of red and 500 kg of blue fluorescent sand were deployed on both bank flanks of the Middelkerke Bank. The results, however biased, showed that sand is being moved both along and across the bank in both northeast and southwest directions. The tracer deployed on the northwestern flank showed a preferred movement in a northeastern direction (direction of maximum flood current).
- One experiment with magnetic sand was carried out on the beach of Nieuwpoort (VAN DER POST et al. (1994)). Approximately 100 kg of tracer material was placed in a shallow pit on the beach. Magnetic susceptibility measurements, carried out with a Bartington Susceptibility meter and surface loop sensor, took place in the centre of grid cells defined around the pit during 23 days. The results showed that the majority of the mobilised tracer material was transported and deposited in a southwesterly direction.

Table II. Results of radio-active, fluorescent and magnetic tracer experiments (n.a. : not applicable)

	Location	*Position Easting - Northing*		*Period measurement*	*Direct. Resid. trans*	*Transport (m^3/m/day)*	*Reference*
Radioactive tracers	Western Appelzak	519739	5690107	Okt 77-Dec 77	N75°E	2.5	Reference 1
	Eastern Appelzak	522511	5691051	Okt 77-Jan 78	N185°E	0.5	Idem
	North of Appelzak	522253	5691575	Okt 77-Jan 78	N75°E	0.1	Idem
	West of Paardenmarkt	516619	5689171	Dec 77-Mar 78	N160°E	0.05	Idem
	Belgian-Dutch border	524557	5692339	Dec 77-Mar 78	-	negligible	Idem
	Wielingen	515098	5692504	Feb 78-May 78	N232°E	1.8	Idem
	W of Pas van het Zand	509970	5689432	Feb 78-May 78	N275°E	0.04	Idem
	North Wandelaar	502294	5695080	Oct 78-Jan 79	N41-221°E	negligible	Idem
	Access channel Zeebrugge	500252	5696698	Oct 78-Jan 79	-	negligible	Idem
	Akkaert Bank	493798	5696154	Oct 78-Jan 79	N50-230°E	negligible	Idem
	Sierra Ventana (STI1)	505238	5700118	Oct 78-Jan 79	N45°E	0.002	Idem
	Dumping site STI2	502138	5702029	Oct 78-Jan 79	-	0.002	Idem
	Westdyck	424198	5665326	Sep 86-Feb 87	E/NE	0.03	BECK et al. (1991)
Fluorescent tracers	Albert beach	518920	5688899	Sep 77-Oct 77	E	3.6	Reference 2
	Lekkerbek beach	522281	5690025	Oct 77-Nov. 77	E	3.5 to 24.5	Idem
	Heist beach	517181	5688152	Jan 78	E	7.0 to 27.6	Idem
	Bredene beach	unknown		Feb 94-Mar 94	Onshore/E	n.a.	IGNACIO RUIZ GARCIA (1994)
	Nieuwpoort beach	unknown		Feb 94-Mar 94	NE	n.a.	O'CONNOR (1996)
	Middelkerke Bank (W flank)	568518	482092	Dec 92-Jul 94	NE	n.a.	WILLIAMS ET AL. (2000)
	Middelkerke Bank (E flank)	568481	482691	Dec 92-Jul 94	n.a.	n.a.	WILLIAMS ET AL. (2000)
	Nieuwpoort beach	W of the pier		Apr. 95 (10-14)	SW	n.a.	BROEKAERT (1995); MOERKERKE (1995)
*	Nieuwpoort beach	unknown		May 1993	SW	n.a.	O'CONNOR (1996)

* Magnetic tracers

Reference 1: TIJDELIJKE VERENIGING ZEEBOUW ZEEZAND and HAECON-ZEEBRUGGE STUDIEGROEP T.V.Z.2. (1978b); BASTIN et al. (1983)

Reference 2: TIJDELIJKE VERENIGING ZEEBOUW ZEEZAND and HAECON-ZEEBRUGGE STUDIEGROEP T.V.Z.2. (1979); BASTIN et al. (1983)

Suspension load tracers

Although the present study focuses on the residual sandy bedload transport, details concerning the results of residual suspension load measurements are given hereafter.

Six injections of re-circulation tracers were carried out on the Belgian shelf. A re-circulation towards the coastal area was found where the sediment seemed to be trapped and a limited exchange with the offshore was advanced. A transport of the suspended sediment in a northeast direction seemed to be slightly more important than the transport in southwest direction.

The radioactive tracer experiments have been used for validation of a sediment transport model (VAN DEN EYNDE (2001)). The main conclusion was that the tracer results give some first indications of the suspension transport, but they had to be used with precaution, because 1) during bottom sampling, the tidal cycle variation was not taken into account; 2) most of the bottom samples were taken near the coast and not much information on the dispersion of the matter in the open sea was available due to bad weather; 3) many samples were taken in the harbours themselves, where local effects play an important role; 4) from the calculation of activity balances, it appears that in some cases only a very small amount of the matter is found back during the detection campaigns. This implies that the complete dispersion of the material cannot be derived from these results.

Natural tracers

Salinity

- As already mentioned, it is possible to trace large scale (and long term) residual water movement by using natural components of the seawater. Salinity or rather patches of fresh water such as the ones created near the Rhine-Meuse estuary, become eventually isolated from further influence of river discharge and can be used as a large scale tracer. VISSER (1989) measured surface salinity during the years 1976 to 1983 on intervals of 14 days at a number of locations positioned along ten cross shore sections ranging from 1 to 70 km offshore. Although the stations are located on the Dutch shelf, the results of the southern cross lines can be extrapolated to the Belgian shelf. In the Dutch coastal area (between 0 and 30 km offshore) the residual movement increases, going NNE-ward, from almost zero near the Belgian coast to about 6 cm/s near the isle of Texel. At a distance of 70 km off the Dutch coast the salinity data reveal an eight-year average residual velocity of 3 cm/s, NNE-ward. This technique has the advantage that it allows the deduction of long-term residual movement which is nearly impossible to achieve from current meters and drifter experiments as the results of these techniques will be biased by local residual currents induced by variable wind and waves.

Suspended matter

- VISSER (1989) studied salinity and turbidity based on the same data set and indirectly comment on residual movement deduced from the displacement of a suspended matter minimum. The authors mention the existence of high amounts of suspended matter in the vicinity of the Flemish Banks that act during wintertime as a source to the Dutch coast.

Temperature

- JEGOU and SALOMON (1991) advanced the idea of using the superficial water temperature detected on the thermal infrared imagery of NOAA AVHRR (Very High Resolution Radiometer) as a tracer. In a study of the English Channel the imagery is compared with the results of a 2-D numerical model. Residual water movements could be detected on a time scale of some weeks especially at the end of the winter period when thermal exchanges are reduced and the vertical water structure is homogeneous.

Conclusion

Tracer experiments have always been a popular technique to derive the residual bedload transport directions. The principal reasons for this success are (i) the technique is inexpensive to use (with the exception of the radio-active tracer), (ii) the results are normally easy to interpret and unambiguous and (iii) the logistics necessary to carry out the tracer operation are (at least on land) practical and uncomplicated. The extensive sediment sampling on the beaches can even be eliminated or supplemented by photometric measurements of marked particle concentration in the case of fluorescent tracers.

The technique is however not always successful as certain factors can prevent a normal dispersion of the tracer particles. If the area in which the experiments takes place is subject to a sediment accretion the tracer substance can be covered with sediment which makes it unavailable for transport. This phenomenon has been observed on beaches when the tracer experiment took place during periods of calm weather conditions. However in most cases the tracer experiment reveals useful information on the residual transport directions.

Fluorescent tracer experiments in the offshore have to rely on extensive sampling operations, which makes the method rather expensive. In this case other tracer methods, in which the detection of the marked particles can take place directly on the seabed by using a detection unit mounted on a sledge, should be favoured. As radio-active tracers are largely discouraged because of health and safety reasons, magnetic tracers should be considered for this type of research.

3.3.3. Residual transport directions based on sedimentological differentiations

Residual transport directions based on a sediment trend analysis (STA)

Many authors have tried to use variations in the areal pattern of grain-size parameters for the determination of residual sediment transport paths. STRIDE (1963) found a progressive decrease in grain-size for the uppermost loose sediments in a northeastern direction in the Southern North Sea and deduced that this direction would correspond with the main residual sediment transport direction.

McLAREN (1981), McLAREN and BOWLES (1985) elaborated a statistical approach to determine the sediment transport directions along a line by examining the sedimentological parameters of all possible pairs of samples on a sample line. GAO and COLLINS (1992) proposed a two-dimensional approach suitable for samples taken in a grid. In this case coarseness, sorting and skewness of each sample are compared with the same parameters of its eight neighbouring samples. A unit length vector is then drawn for each direction corresponding to a specific defined transport trend followed by a summation of similar trend vectors producing a single vector. Finally a filtering operation is applied to remove or reduce any remaining noise.

The principal question when using this technique is which transport trend has to be considered ? Answers have been formulated based on theoretical concepts (McLAREN (1981)) or on empirical grounds (GAO and COLLINS (1994)). GAO et al. (1994) used a straightforward approach in which each possible trend (14 trends exist when considering three grain-size parameters) was considered and compared with residual transport paths deduced from the asymmetry of bedforms. Two important conclusions could be drawn: (i) trends in which the sorting is worsening along the considered transport paths have little similarity with the transport patterns deduced from other methods and (ii) a high degree of similarity with the residual transport patterns is obtained when using the combined trend of FB- (Finer, Better sorted and more negative skewness) and CB+ (Coarser, Better sorted and more positive skewness).

The sediment trend analysis (STA) has been used on the BCS in studies on three different space scales. A very large scale STA (HAECON (1992)) was carried out on the southern North Sea; two studies were carried on the scale of a coastal system (HONEYBUN 1999, CHARLET (2001)) and some smaller studies used the STA to study residual sediment transport paths on sandbank sections (LANCKNEUS et al. (1992), GAO et al. (1994), VAN LANCKER (1993), LANCKNEUS et al. (1993), VANWESENBEECK and LANCKNEUS (2000)). Most of the studies compared the results of the STA with the residual transport paths deduced from other techniques.

The STA carried out on the southern North Sea used four sediment trends (FB-, CB+, FB+, CB-). The results show clearly that a distinction can be made between a coastal and an offshore area. In the coastal area transport vectors are oriented towards the coast while in the offshore area a northeastern transport is dominant. However in some areas such as the Flemish Banks opposite transport directions (northeast and southwest) occur.

The results of the studies carried out on smaller areas show generally a good similarity with the directions deduced from bedform analysis. On the northern Kwinte Bank for example (GAO et al. (1994)), the STA suggested sediment transport in both adjacent swales parallel to the bank's axis and in opposite directions (to the northeast in the Kwinte swale and to the southwest in the Negenvaam). Furthermore STA indicated as well a component of sediment transport from both bank flanks towards the crest of the bank. These results are in good agreement with the results of the numerous bathymetric, side-scan sonar and current measurements that took place on the Kwinte Bank during more than a decade.

Residual transport directions based on a fraction analysis

To gain more insight into the processes governing the physical functioning of a coastal system, it is advisable to study the distribution of the different grain-size classes individually. This should only be done in an environment where the surficial sediments are mutually related and the change in the frequency of occurrence of the grain-size classes can be studied in relation to the morphology. The analysis is especially valuable in areas with no bedforms. It can be used to confirm and to get more confidence in the results of a sediment trend analysis.

VAN LANCKER (1999) performed a fraction analysis in the western near coastal area. From this, it was deduced that the surficial sediments were mainly subjected to 3 processes corresponding with the residual transport over a sandbank: an enrichment of coarser fractions at the foot of the sandbanks originating from the swales, an upslope fining upward transport and finally a winnowing or washing out of the finer fractions higher up the sandbanks.

Moreover, a fraction analysis is recommended if sequential samplings are carried out. VAN LANCKER (1999) showed that in the case of an active sediment transport system, the seafloor will be coarsest under calm weather conditions as the finer sandy sediments have been redistributed whilst under rougher conditions there is an active input of finer sandy sediments; hence the surficial sediments are generally finer.

Conclusions

The STA technique was used in different studies on the BCS where it was applied on the entire southern North Sea, along the western and eastern near coastal area and on sections of the Kwinte Bank, Middelkerke Bank, Goote Bank and the Ravelingen.

The results show that this technique remains valuable to study sediment transport directions. However to deduce residual transport directions, it should be compared and integrated with complementary techniques. Moreover, it is advisable to have some prior knowledge of the hydrodynamic environment.

A problem that has to be tackled is the grid interval of the samples. Like other techniques the results of the STA can be applied on different space scales. Samples with an interval of 500 m on a section of a sandbank can reveal the transport patterns on this particular scale (for example convergence of sand streams in opposite directions towards the bank's axis) which however can be completely different when considering the transport pattern on a much larger scale such as the entire shelf (which could be from southwest to northeast). A superposition of grain-size trends of different space scales, like the trend corresponding to an individual sandbank and the trend corresponding to the southern North Sea, will undoubtedly cause complications in the interpretation of the STA. Therefore, an STA is preferentially carried out in an environment where the surficial sediments are equally influenced by the hydrodynamical agents as to avoid time constraints, which may strongly bias the results. Moreover, the most significant results are expected if only one depositional environment is taken into account.

A fraction analysis is recommended if samples are obtained in a well-confined depositional environment and if the samples are taken in relation to morphological changes.

3.3.4. Residual transport directions based on current and suspended sediment concentration measurements

Introduction

One of the earlier techniques to measure the residual movement of water and suspended matter was to carry out punctual measurements of current and sediment concentrations along a vertical profile at certain depth intervals every half hour. The current velocity would be measured by an Ott meter and sediment concentration would be determined by taking water samples in Nansen bottles. This technique was time and labour consuming and therefore it was mostly restricted to relative short time intervals such as one tidal cycle. Integration of the velocity component by the concentration values would give the total sediment flux at a certain time. Adding all calculated fluxes would give the residual sediment transport for the tidal cycle. It is clear that the obtained result only represents the residual movement over a very short period and that this result could easily be influenced by a dominant hydro-meteorological condition. Table III presents a number of these results, which were all obtained in the framework of the construction of the extension of the harbour of Zeebrugge.

Although the data of Table III are valuable and give an interesting insight in the order of magnitude of the sediment transport quantities, it has to be taken in account that the sediment fluxes are subject to strong fluctuations in space and time. Therefore care has to be taken when attempts are made to reconstruct a reliable picture on sediment transport valid for different space and time scales when it is based on short-term observations.

Table III. Results of current and sediment concentration measurements (TIJDELIJKE VERENIGING ZEEBOUW ZEEZAND and HAECON-ZEEBRUGGE STUDIEGROEP T.V.Z.2. (1978a); HAECON (1982b))

Location	*Easting – Northing*		*Period*	*Res. Trans°*	*Ton/m/ day*
Scheur Oost	528933	5693612	1 tide (August 77)	N250°E	4.0
Scheur Oost	528679	5694229	1 tide (August 77)	N260°E	83.0
Scheur Oost	528423	5694907	1 tide (August 77)	-	-
Eastern Appelzak	525431	5686805	1 tide (August 77)	N67°E	6.0
Eastern Wielingen	525035	5692510	1 tide (August 77)	N250°E	31.0
Eastern Wielingen	524702	5693312	1 tide (August 77)	-	-
Eastern Wielingen	524370	5694144	1 tide (August 77)	-	-
Central Appelzak	521583	5690425	1 tide (August 77)	N208°E	7.0
Eastern Paardenmarkt	521290	5691134	1 tide (August 77)	N77°E	23.0
Eastern Paardenmarkt	520880	5692152	1 tide (August 77)	N276°E	19.0
Eastern Wielingen	520411	5693324	1 tide (August 77)	-	-
Western Appelzak	518989	5689376	1 tide (August 77)	N132°E	10.0
Western Paardenmarkt	518708	5690077	1 tide (August 77)	N78°E	4.0
Western Paardenmarkt	518221	5691275	1 tide (August 77)	N253°E	26.0
Western Wielingen	517707	5692546	1 tide (August 77)	-	-
Pas van het Zand	513328	5689930	18/07/75 (neap)	N263°E	1.5
Pas van het Zand	513328	5689930	29/07/75 (middle)	N234°E	9.0
Pas van het Zand	513006	5691124	17/07/75 (neap)	N246°E	11.8
Pas van het Zand	513006	5691124	28/07/75 (middle)	N241°E	18.4
Pas van het Zand	513128	5689927	04/07/76 (middle)	N99°E	7.6
Pas van het Zand	513128	5689927	28/07/76 (spring)	N246°E	12.4
Pas van het Zand	513872	5690240	05/08/76 (middle)	N300°E	6.4
Pas van het Zand	513872	5690240	29/07/76 (spring)	N254°E	3.2
Pas van het Zand	513742	5689138	02/07/76 (middle)	N224°E	6.1
Pas van het Zand	514786	5689457	03/07/76 (middle)	N115°E	27.0
Pas van het Zand	512116	5690608	27/07/76 (spring)	N253°E	10.4
Pas van het Zand	512317	5690512	16/07/76 (middle)	N260°E	9.0
Pas van het Zand	513310	5690880	26/07/76 (middle)	N260°E	5.4
Pas van het Zand	510173	5692971	11/08/76 (spring)	N84°E	2.0
Pas van het Zand	510868	5693234	12/08/76 (spring)	N87°E	0.6

Recent techniques

On the BCS, advanced measuring techniques were used on a longer term in the framework of the MOBAG 2000 project. This project aimed at an evaluation and understanding of the environmental impact of increased turbidity values caused by dredging and relocation operations on the Belgian shelf (CLAEYS (2000); VAN PARYS et al. (2001)). Both the natural background turbidity and the turbidity plumes caused by relocation processes on the two dumping grounds Zeebrugge East and S1 were studied with four frames positioned on the seabottom. Two frames were equipped with four optical backscatter sensors deployed on different heights in the water column and two frames were equipped with an acoustic doppler current profiler, measuring current velocity and direction in cells of 0.5 m from the seabottom to the water surface. Table IV and y present the results of residual suspension transport on the four frame locations of the dumping ground Zeebrugge East and S1 (MAGELAS (2001)).

Table IV. Results of mean suspension transport for ebb and flood over three tidal cycles measured on the dumping ground Zeebrugge East; figures of residual transport are given too (a negative number equals transport towards the southwest, a positive number towards the northeast) (MAGELAS (2001)).

		Location 1	*Location 2*	*Location 3*	*Location 4*	*Mean residual transport (ton/m)*
Position	Easting	517580	518930	519380	519696	
	Northing	5692060	5692290	5692380	5692402	
Spring tide (ton/m)	Ebb	-88	-60	-48	-75	
	Flood	107	98	94	115	
	Residual	19	38	46	40	36
Middle tide (ton/m)	Ebb	-41	-30	-20	-32	
	Flood	41	33	20	28	
	Residual	0	3	0	-2	0
Neap tide (ton/m)	Ebb	-26	-18	-11	-17	
	Flood	41	21	28	22	
	Residual	15	3	17	5	10
Mean residual transport (ton/m)		11	15	21	14	24

This type of measurement allows collecting information during several weeks, which makes it possible to study current velocities and sediment concentrations during an entire spring-neap tidal cycle. If hydro-meteorological data is obtained during the same period, relations between suspension concentrations and other parameters such as wave height and wind velocity can be studied.

From Table V it can be deduced that the residual transport on the dumping ground Zeebrugge East is directed towards the northeast; the transport of sediment in suspension during a spring tide is three to five times more important than during neap tide.

Table V. Results of mean suspension transport for ebb and flood over two tidal cycles measured on the dumping ground S1; figures of residual transport are given too. (a negative number equals transport towards the southwest, a positive number towards the northeast) (MAGELAS (2001)).

		Location 1	*Location 2*	*Location 3*	*Location 4*	*Mean residual transport (ton/m)*
Position	Easting Northing	500186 5699756	500597 5700052	500960 5700282	502362 5700733	
Spring tide (ton/m)	Ebb Flood Residual	-9 16 7	-10 16 6	-12 23 11	No data	8
Neap tide (ton/m)	Ebb Flood Residual	-2 5 3	-3 8 5	-3 7 4	No data	4
Mean residual transport (ton/m)		5	6	8	No data	6

The residual transport on dumping ground S1 is as well directed towards the northeast. The residual transport during spring tide is two to three times more important than during neap tide. Comparison between Table IV and 5 shows clearly that the quantities of sediment in suspension that are moved residually can differ substantially from one location to another (17 km between the two dumping grounds).

Conclusions

When studying the residual transport based on measurements over one or a few tidal cycles one should realise that they can only give information for the considered period and that they cannot be used to derive long-term sediment transport patterns. Ship-borne measurements are usually limited to one point and one tidal cycle. Advantage of ship-borne measurements is the very high time-resolution (e.g. every 1-10 sec), which is possible because the instrument is not in stand-alone mode. The disadvantage is the relatively poor vertical resolution. The bottom layer (lowest 2-3 m) is not measured. Installations of bottom frames allow measuring during longer periods and have the advantage of a good resolution of the bottom layer.

On the BCS, bottom frame measurements have been used to study small-scale processes (STABLE-II) and were deployed during 1 week up to 1 month. However, the interpretation of the data can be complex because of variation in bed position (bed form migration, tilting of the frame).

3.3.5. Residual transport directions based on sediment transport models

Sediment transport modelling is still inexact because it depends on interrelated processes, which are often not well understood or measured (SOULSBY (1997)). Error and uncertainties arise because the prediction method does not include all the relevant processes involved, because of incomplete understanding or imprecise formulation of the processes included, because of errors in measuring the input and the 'observed output' values as well as spatial and temporal variations in sediment properties. Despite the great level of inaccuracy, models are however a very valuable tool to deduce sediment transport results over large areas and over long time periods.

The numerical sediment transport models applied to the BCS can be divided in suspended load and in total load models. Total load models solve a so-called total load formula comprising a bedload and suspended load contribution (see DJENIDI and RONDAY (1992)) or alternatively the total sediment transport rate may be given by an empirical formula (VAN DEN EYNDE and OZER (1993); VAN DEN EYNDE (2001)). Suspension transport models can be presented for the mud fraction (FETTWEIS and VAN DEN EYNDE (2000a; 2000b; 2001a; 2001b)) and for fine sand and silt (VAN DEN EYNDE (1999a)). On the BCS uncertainties arise because of the occurrence of cohesive fractions.

Cohesive sediments are often considered in four different states: suspension, fluid mud, partially consolidated bed and settled bed. The processes responsible for the formation of and the processes acting on the suspended sediment state are deposition, erosion, aggregation and flocculation. Consolidation of a cohesive bed is defined as the gradual expulsion of the interstitial water resulting in an increase of the bed density and the bed strength with time. The problem of cohesive sediment transport is the interaction of many complex processes (still now poorly understood) and the different scales involved. Therefore, numerical models should be complemented with experimental data for calibration and validation and need more detail which is often difficult to establish in regional models (TOORMAN (2001)).

The cohesive sediment transport models of the BCS are regional 'engineering' type models containing many simplifications (due to the limited knowledge of the physics and the physical environment). The turbulence fields, parameterised as subscale phenomena, the bed composition and the boundary conditions are poorly known, due to a lack of field data (erosion and deposition as a function of sediment composition, transport, consolidation) and are simulated using simplified relations without taking into account biological processes.

The BCS models are thus only approximate and they should therefore not be used as the ultimate tool to predict the behaviour of mud but rather as an instrument for a better understanding of some of the aspects of mud transport. It must therefore be mentioned that these models, being limited in time and space scales, with only some basic cohesive sediment processes incorporated and based on the input provided by a simplified hydrodynamic model (in the sense of 2D depth-averaged), can only simulate long term transport phenomena with low accuracy. Furthermore as is pointed out by TEISSON (1994), validation of the models is difficult, since the predictive capabilities rely on the formulation of cohesive sediment transport processes, which are site-specific and not general.

3.4. Evaluation criteria

3.4.1. Introduction

In the critical analysis of data and methods used (Paragraph 3.3), it has been emphasised that the time and space scale of the different results can be quite different one from another and that care has to be taken when results obtained with different techniques (or even with the same technique used on different scales) are compared. It is therefore interesting to try to classify all used methods on the BCS in the various time and space scales.

3.4.2. Space and time scales

Concerning the time scale, a distinction was made between four different categories: (i) the micro scale (processes measured over a lapse of hours up to days), (ii) the meso scale (lapse of days to weeks), (iii) the macro scale (lapse of weeks to months) and (iv) the mega scale (lapse of years to decades). Processes on an event scale or generally over shorter periods than the ones mentioned in the micro scale are not taken into consideration as this report merely focuses on the residual sediment transport on a larger scale.

For the space scale, four categories were chosen: (i) the micro scale (in which the result of the process has an impact on a structure with dimensions of 0.1 to 1 m), (ii) the meso scale (between 1 and 100 m), (iii) the macro scale (between 100 m and 1 km) and the mega scale (between 1 and 100 km).
The techniques mentioned in the former paragraphs were classified according to these time and space scales (Table VI). Additionally, a distinction was made if the technique was applied on the beach or offshore.

Table VI. Classification of sediment transport methods according to time and space scales ; techniques written in italic have not been applied on the BCS.

<table>
<tr><td colspan="3" rowspan="2"></td><td colspan="4">Time scale</td></tr>
<tr><td>Micro scale
Hours-days</td><td>Meso scale
Days-weeks</td><td>Macro scale
Weeks-months</td><td>Mega scale
Years-decades</td></tr>
<tr><td rowspan="8">Space scale</td><td rowspan="2">Micro scale
0.1 – 1 m</td><td>Offshore</td><td rowspan="2">Sand ripple profiler</td><td></td><td></td><td></td></tr>
<tr><td>Beach</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Meso scale
1 - 100 m</td><td>Offshore</td><td>Suspension measurements</td><td colspan="2">Suspension measurement
Fluorescent tracer</td><td></td></tr>
<tr><td>Beach</td><td></td><td>Fluorescent tracer
Magnetic tracer</td><td>Fluorescent tracer</td><td></td></tr>
<tr><td rowspan="2">Macro scale
100 m – 1 km</td><td>Offshore</td><td></td><td>Small dunes</td><td>Radio-active tracer (bedload)
STA
Large dunes</td><td>Wreck marks</td></tr>
<tr><td>Beach</td><td></td><td>Fluorescent tracer</td><td></td><td></td></tr>
<tr><td rowspan="2">Mega scale
1 – 100 km</td><td>Offshore</td><td>Suspension measurement with aeroplane registrations</td><td></td><td>Temperature as a tracer
Radio-active tracer (susp. load)
Suspension as a tracer
STA</td><td>Large dunes
Salinity as a tracer
STA
Fluorescent tracer (?)</td></tr>
<tr><td>Beach</td><td></td><td></td><td></td><td></td></tr>
</table>

3.4.3. Space and time scales of the considered techniques

It was demonstrated that the dominant tidal current basically causes the asymmetry of the bedforms on the sandbanks albeit well or not influenced by hydro-meteorological effects. As the latter may have a pronounced effect on the asymmetry of the dunes, it seems plausible that the time scale, during which the residual transport deductions are valid, is of the same order of the hydro-meteorological events. This would mean that the observations on small dunes would be usually valid over a time scale of a few days to a few weeks (meso scale).

Many authors however apply a much larger time scale and even use the asymmetry of large dunes in long-term predictions (macro to mega scale). *Can this be done and, if the answer is yes, under which circumstances?*

The analysis has shown that the smallest large dunes are the first ones to switch their asymmetry when subject to a factor other than the tidal influence and that the asymmetry of the largest features are hardly influenced by external factors. This means that a residual transport analysis based on the asymmetry of the very large dunes can be valid over a lapse of many years (mega scale). A very large dune has such an enormous volume of sediment stored in it that it can be considered stable in a time-scale of years.

If several recordings of bedforms could be obtained through the year, it becomes possible to extract a global, overall picture of the large dunes' asymmetry pattern.

The large dunes described in the analyses mentioned above are mostly located on the flanks and top of the sandbanks. However, large dunes can occur as well in the deeper waters of the swales or on a flat section of the sea floor. They are rare in the swales of the Flemish Banks, but seem to be abundant in the northern part of the Hinder Banks region (DELEU 2001). An exception in the Flemish Bank region is the presence of a large barchan-type dune in the Buiten Ratel swale (extremities pointing to the northeast corresponding to the residual transport direction) (DE MOOR and LANCKNEUS (1988a)). In the near coastal zone, large dunes (up to more than 2 m) occur in the Westdiep swale and north of the Wenduine Bank and north of the Paardenmarkt shoal (VAN LANCKER 1999, VAN LANCKER et al. (2000), CHARLET 2001, VANSTAEN in prep.). They all point dominantly in a northeastern direction. Interestingly, the large dunes north of the Paardenmarkt shoal are flood-dominated in the west, but merely symmetrical to slightly ebb-dominant to the east. This will be discussed in Paragraph 4.

Generally, large features located in relatively deeper water are probably more stable than the smaller dunes on the flanks of the sandbank and therefore more suitable to deduce longer-term transport directions. Similarly, STRIDE (1970) used large dunes with an averaged height of 4 to 5 m and occurring on a flat sea bottom in deep waters (around 30 m) to deduce residual transport directions. Even if only one recording is made of these bedforms, it are likely more indicative of the longer-term residual transport direction.

Fluorescent tracers have been used both on the beach and offshore. If the tracer experiment on the beach takes place in an active hydrodynamic environment (and if the tracer is not buried by sand during a period of accretion), the sand movement can be detected on a meso time scale. Only one fluorescent tracer experiment took place on the BCS (Middelkerke Bank). The results were largely biased as most of the tracer was buried after its release and weather conditions didn't allow obtaining samples in a regular grid, which makes quantification extremely difficult. It remains difficult to evaluate whether this technique can be used on a macro time scale.

Although now no longer in use, radioactive tracers have the advantage that they can be used to monitor processes in the macro time scale what was proved by the experiments around Zeebrugge. The bedload tracers would reveal a residual transport in the meso space scale and the suspension load tracers could even be used in the mega space scale. The radioactive bedload tracers can be detected by using a sensor attached to a sledge allowing continuous measurements along tracks and no time-consuming sampling operations are involved. On the other hand water samples have to be taken when working with radioactive suspension tracers. To conclude radioactive tracers have as important plus-point that results of residual bedload transport can be obtained over a period of several months, which for the moment has never been obtained by using another technique.
Possibly experiments with magnetic tracers could combine the user friendliness of the fluorescent tracer and the results on a macro time scale of the radioactive tracer. Furthermore samples have not to be taken and measurements could be carried out in a continuous way using a towed sensor. This technique however has never been used on the BCS.

Natural tracers such as temperature, salinity and suspension clouds form an additional tool to the artificial tracers. In some cases such as the salinity, the technique can be used to provide information on the largest time (years) and space scale (tens of km) considered. To our knowledge (although salinity measurements are taken on a regular base by many scientific crews), the salinity data on the BCS were never used for a residual transport study. However the technique was used with success on the Dutch shelf because the Rhine-Meuse and the Scheldt estuary created the necessary patches of fresh water to be monitored. If such patches of large dimensions were lacking on our shelf, this technique would be of no use.

The current and suspended sediment concentration measurements can provide information from the micro time scale up to the macro time scale depending on the duration of deployment. It needs emphasis that both current measurements and suspended sediment concentrations are highly dependent on the hydro-meteorological conditions, hence an extrapolation of the results obtained over one tidal cycle to a larger time scale can induce considerable errors.

A series of continuous measurements with OBS and ADcP during one month on the dumping grounds Zeebrugge East and S1 carried out in the framework of the MOBAG 2000 project showed clearly that the sediment transport during spring tide could be 2 to 5 times higher than during neap tide. Storms can cause as well an increase in suspended sediment and the sediment concentrations monitored during the storm events were of the same order as during spring tide. Similar measurements together with aeroplane multispectral scanner registrations (a.o. EUROSENSE (1994a)) have the advantage of providing spatial information and if they are combined with a high-resolution hydrodynamic model, suspended sediment transport can be more realistically calculated.

The Sediment Trend Analysis can provide information concerning residual sediment transport on a macro to mega time scale depending on the considered sampling interval. The results of a STA based on samples taken on a section of a sandbank would be valid for a space scale similar to the dimensions of the sampling grid. However, it is not very clear what time scale would correspond to these results as little is known from the impact of punctual events such as storms on the spatial distribution of the grain-size parameters. As bathymetric measurements showed that storm events could lower the top of the large bedforms superposed on the bank top and even lower the bank top surface (HOUTHUYS et al. (1994)), it is probable that the eroded sediment is transported over a certain distance before it settles in the adjacent swales. The grain-size characteristics such as mean, sorting and skewness of the sediments will at that moment be at least slightly altered but this alteration must be of short duration as the tidal currents must be able to redistribute the sediment quite fast in function of the banks' morphology. A STA carried out on the BCS would have the advantage that its residual transport results would be valid in the mega time scale, still care is needed in the validation of the results as obviously a mix of different time and space scales are involved.

To obtain more insight into the time-scales structuring depositional environments, it remains highly advisable to monitor specific areas at regular interval and this in relation to changing hydro-meteorological conditions. The areas are preferentially well constraint meaning that they can be regarded representative of a larger sedimentary system and avoiding localised effects. The more these prerequisites are respected; the most likely significant trends can be deduced regarding sediment dynamics versus hydro-meteorological conditions. On the basis of successive bathymetric surveys, VAN LANCKER (1999) demonstrated that a clear in relation could be found between differing sediment volumes and changes in hydro-meteorological conditions. Figure 15 shows that this relation is significant and can be quantified (VAN LANCKER, in prep.). The same can be done on the basis of sequential sediment sampling of the surficial sediments, but again it is of utmost importance to choose the right areas, to sample in function of morphological changes with a good quality control on the exact positioning of the sampling points.

It is thought that monitoring is preferentially performed in bedload convergence areas as these likely capture sand from a larger sedimentary system and are mostly well constraint. It is hoped that the synthesis map compiled in the framework of this project can help in choosing these areas.

3.5. Sediment budgeting

DRONKERS et al. (1990) made some calculations on the suspended sediment transport in the Southern North Sea with emphasis on the Dutch coast. An average flow in northern direction with a residual transport velocity of 3-5 cm/s was considered. Sediment concentrations were derived from the available vertical profiles that resulted in vertically averaged concentrations approximately 1.5 times higher than the surface concentrations. Using these figures the average alongshore sediment transport was computed which amounted to 15 x 10^6 ton/year. However the input of sediment in Dutch waters (of which (2.5-5) x 10^6 ton/year is coming through the Channel and (1-2) x 10^6 ton/year originating from the erosion of the Flemish Banks and the surrounding seafloor) is believed to be of the order of (3-6.7) 10^6 ton/year. After taking into consideration a number of factors such as the density influence on the vertical residual flow profile, the tide-induced residual transport and the effect of fluid mudflows, the computed value was reduced to 5 x 10^6 ton/year.

Using the existing data it is difficult to set up a quantitative sediment balance (sand fraction) of the BCS. Quantitative data exist however for the human activities on the BCS, such as the dredging works, the study of the dumping place B&W S1 and data on sand extraction and beach nourishment (FETTWEIS and VAN DEN EYNDE (1999)). The following items can be mentioned:

- Yearly about 1.4x10^6 t dry matter (TDM) of sand is dredged in the navigation channels, hereof 1x10^6 TDM is dumped on B&W S1 (80%) and B&W S2 (20%) and 0.4x10^6 TDM is used for beach nourishment.
- Measurements on B&W S1 indicate that 80-90% of the dumped sand stays on the dumping place. The results of a Sediment Trend Analysis (STA) suggest that the remaining 10-20% are transported back to the navigation channels Scheur Oost/West (HAECON (1994)). This corresponds to replenishment for the dredging year 1997 of 0.08-0.16 TDM (15-30%) from B&W S1. The same STA results indicate that the most important replenishment of the navigation channels is from sand transport from the west (Wenduine Bank, Wandelaar).
- Erosion occurs along some parts of the Belgian coast. During the nineties about 1.1x10^6 TDM/yr of sand have been extracted for beach nourishment works.
- The Flemish Banks are stable. After erosive periods (storm or sand extraction) a regeneration of the bank seems to occur. It should be investigated whether the beaches are a possible source for the replenishment of the banks where the sand is extracted.
- Every year 2.5x10^6 TDM of sand is extracted (90% on the Kwinte Bank).
- From national and international investigations, a global transit of 5 x10^6 to 10x10^6 TDM/yr is estimated as being transported along the French, Belgian and Dutch coast in a NE direction (MINISTERIE VAN DE VLAAMSE GEMEENSCHAP (1994)). FETTWEIS and VAN DEN EYNDE (1999) report an estimate of 20x10^6 TDM/yr for suspended matter.

On the basis of the calculations of VAN LANCKER (1999), the suspended load was calculated averaged over a spring, mid and neap tidal cycle, taken into account the in-situ sediments. The calculations were based on current meter data provided by Waterways Coast Division and were solely recovered under calm weather conditions. Annex 1 gives the calculated amount of suspended load (tonnes/m/day), these are also indicated on the synthesis map. The values obtained were in the same order of magnitude as the sediment fluxes obtained from an acoustical backscattering sensor deployed along the steep side and on the southern part of the

Middelkerke Bank over the period 16/02-29/03 1994 (VINCENT et al. (1998)). Most interestingly, this study also revealed information on the grain-size of the sand transported as bedload and as suspended load. On the basis of a 40 days measuring period of suspended sand profiles and current meter data, they came to the following conclusions regarding sand transport rates:

- The sand transport rate on the steep slope of the Middelkerke Bank (0.9 tonnes/m/day up to 0.3 m above the bed) was 10 times that of the southern end of the bank (0.05 tonnes/m/day) and was up-slope at 25 degrees to the bank axis, in the direction of the major axis of the tidal ellipse;
- The transport on the steep slope was mainly in the size range of 100-140 µm which did not occur in any significant proportion in samples of the sea bed at that site leading to the conclusion that this fraction is likely advected from deeper water (SE);
- Excluding the finer component the transport rates of coarser sand (>200 µm) at the two sites were similar over the 40 days period;
- The transport rates are consistent with a time-scale of 100-1000 years for the formation of the Middelkerke Bank.

3.6. Synthesis map of the natural sand transport on the BCS

A synthesis map has been drawn to compile the existing information related to the characterisation of the natural sand transport on the Belgian continental shelf (Annex 2).

The map indicates the general nature of the surficial sediments of the BCS grouped into the occurrence of very fine, fine and medium sand based on the median grain-size of the sand fraction. At selected sampling locations, the sediment composition is marked using the sediment classes of Folk & Ward as previously described.

Geologically, areas are indicated where the thickness of the quaternary deposits is less than 2.5 m as these sediments might take part in the sediment transport process.

This information is superimposed by the most recent bathymetrical data provided by the Waterways Coast division of the Ministry of the Flemish Community.

Subsequently, all available information on the occurrence of large dunes was added. Most of the data described in Paragraph 3.1.3. was re-evaluated and compiled to height distribution maps of the larger dunes. Additionally, the crest lines of the large dunes, deduced from side-scan sonar or multibeam recordings, were digitised or imported if digital information was available and were used to deduce residual sediment transport directions.

It has to be taken into account that the compilation of bedform data involved many different datasets and cover a time span of many years. Therefore an overall compilation will never be a single moment representation and contradictions from one area to another can occur as both areas could have been surveyed under completely different hydro-meteorological conditions. Moreover, the critical analysis has shown that hydro-meteorological conditions will mainly influence the asymmetry of the (smaller) large dunes and not the location of the crest lines. When sufficient dimensional information was known, classes of heights were indicated superimposed by the strike of the crest lines of the large dunes.

To illustrate the hydrodynamics of the BCS, current ellipses have been selected based on modelling results on a 750 m grid resolution. Additionally, locations are indicated where current meter or other hydrodynamic data has been collected.

Finally, a variety of arrows are drawn indicative of sediment transport directions. A distinction is made between transport vectors based on geo-environmental methods and those based on in-situ sediment transport measurements and on modelling results.

The geo-environmentally based residual sediment transport vectors are drawn on the basis of the direction of the steep slope of the large dunes, albeit generalised. Apart from the available side-scan sonar and multibeam data, the position of crest points was also deduced from single beam bathymetric recordings. The strike of the bedforms was only indicated if this information was available. In the near coastal area comprising the Nieuwpoort Bank and Stroombank residual sediment transport vectors have also been drawn on the basis of generally valid grain-size trends. This was done, as bedforms are scarce. Slightly veering transport vectors relative to the global NE directed sediment transport represent local transport related to the dynamics of the sandbanks; NE directed vectors merely indicate the regional transport trend.

It was preferred to have vectors with a uniform length for the results from the in-situ sediment transport measurements and from the modelling. If budgets were available, they were recalculated in tonnes/m/day with an annotation within the arrows. The model results represent the total load transport of sand (Mu-SEDIM model) for the year 1999 under the influence of currents alone.

The integrated results are discussed in Paragraph 4.

4. DISCUSSION

4.1. Discussion of the synthesis map

As previously outlined, large dunes can be used to study the residual transport of sediment; hence the synthesis map is at first a compilation of all available bedform information. On a large scale, large dunes merely point in a NE direction in the near coastal zone and in the Flemish Banks region, whilst north and northeast of the Flemish Banks, most of the dunes are ebb-dominated. Interestingly, as well flood- as ebb-dominated very large dunes occur in the northern part of the Hinder Banks region in this equally on the sandbanks as in the swales.

Generally, the sandbanks are characterised by residual transport vectors that tend to be flood-dominated along one flank of the bank, whilst the other flank is merely ebb-dominated. In the near coastal zone, in the Flemish Bank region and along the Zeeland Ridges, the flood tidal current is generally strongest and tends to erode one flank of the bank maintaining the steep slope. Although, the ebb tidal current predominates in the Hinder Banks region, the western flank is also mostly flood-dominated and the eastern flank ebb-dominated. The steep side of the bank corresponds with the flank that is subdued to the highest current-topography interaction.

It is often postulated that sand is moving around a sandbank, but still this remains difficult to prove on the basis of bedform directions. From tracer experiment a circulation around the bank was deduced, still the results are not straightforward. Interestingly, sediment transport modelling does show a clear differentiation along the sandbanks.

In fine sandy areas and definitely in areas predominated by very-fine sandy surficial sediments, bedforms hardly develop. This is also the reason why large dunes are rare in most of the fine sandy to silty swales of the Flemish Banks. Especially in the swales, the cohesive character of the silty sediment fraction changes the e.g. erosive properties of the sediments and thus the sediment transport. Moreover in the swales, the quaternary thickness is often minimal; hence large quantities of sand are lacking for bedform development.

From studies in the near coastal zone (VAN LANCKER 1999; VAN LANCKER ET AL. 2000), it seemed that larger bedforms seem to be constrained to bedload convergence areas with a larger availability of sand. Strikingly, those zones consist of medium sands indicative of recent sediment transport processes. These areas are often minimal in water depth (even 0 m MLLWS) and are not necessarily characterised by higher current velocities than neighbouring locations.

This leads to the question why at some places more sand is available than elsewhere. Studying the pseudo 3D image of Figure 3, most of the sediments seem to be present centrally on the BCS. This is also exemplified by the northern broad tails of the Flemish Banks, the western extremity of the Goote Bank and along the Thornton Bank. An explanation might be found in the fact that these locations are near a bedload-parting zone and might be the first areas to receive sand or able to trap the sand.

4.2. Model results versus field observations

In the critical analysis an overview has been given of the major factors that need to be considered interpreting the results of various field measurements. From this, it could be deduced that a distinction need to be made between equilibrium conditions and conditions largely biased by hydro-meteorological conditions. Especially, towards sediment transport quantification, it is important to know which time scale the values represent and if they are averaged over a spring, mid and neap tidal cycle or not. Moreover, opposed results between model and bedform could also be found (in case a whole area has been surveyed in detail and all the bedforms are known) in the discretisation of sediment transport calculations (the grid size is still much larger than the size of the bedforms) and in the inaccuracy of sediment transport formulas. Further data on the grain size distribution is needed, which is very often lacking and averaged values are used. Since tidal forces are predominantly controlling sediment transport, especially suspended load, the bias around the direction of sediment transport is smaller for long-term measurements but can be high for short-term measurements (i.e. tidal cycle). Still, in any case, it remains extremely difficult to obtain a generally valid quantification of sediment transport; hence only the best estimate can be strived at.

If only averaged values are considered, it is encouraging that the quantification of sediment transport generally lies within the same order of magnitude, even if based on different approaches. An example are the suspended load values obtained from acoustical backscatter measurements (VINCENT et al. (1998)) and the transport vectors calculated on the basis of current meter data from Waterways and Coastal Section combined with other field data (VAN LANCKER ET AL. in prep.).

Towards the quantification of bedload transport, much improvement is reached on the numerical modelling of sediment transport around sandbanks. This is illustrated for the Middelkerke Bank where results from numerical modelling, fluorescent tracers and bedforms analysis point in the same direction.

In the shallowest areas, it becomes much more complex and the results of numerical modelling and bedform observations might be opposed (VAN LANCKER 1999). Crucial is the size of the bedforms and to evaluate the vulnerability of the asymmetry of bedforms to external factors (tidal and changing hydro-meteorological conditions). Still, the shape and the strike of the bedforms can be regarded representative of long-term processes. This has been demonstrated for a large dune field east of the Baland Bank, followed during a 4-years observation period. From this, the shape of the bedforms was remarkably stable even after a variety of hydro-meteo conditions and this in water depths shallower than - 8 m MLLWS (VAN LANCKER 1999). Interestingly, the ebb tidal current also controls the shape of the bedforms regardless of the flood dominance in the near coastal area.

Another example is the area near the French-Belgian border where as well detailed field observations as numerical hydrodynamic model results (residual current) for the same periods are available (OSTC HABITAT). It needs emphasis that the model results are based on calculations on a 750 m grid, still first results on a 250 m grid resolution did not allow to model the complexity of the area. Generally, the model results indicate an overall dominance of the flood tidal current. From field measurements, the large dunes proved to be completely shaped by the ebb tidal current including their asymmetry. Most remarkable, is the seafloor dynamics in the Westdiep swale. Generally, this swale is regarded an important sediment transport pathway whereby even coarse sand can be entrained by the flood tidal current. Still, very-high resolution side-scan sonar imagery revealed current lineation in the deepest part of the swale (likely due to the strong flood tidal current), whilst towards the Trapegeer sandbank, a complex of bedforms occurs that tend to be ebb-dominated. Moreover, higher up the Trapegeer, large dunes are present completely shaped and dominated by the ebb tidal current. VAN LANCKER et al. (2000) interpreted these results as due to the higher resuspension potential of the ebb tidal current that is most effective in the shallow areas, whilst the regional sediment transport on a larger scale is likely flood-dominated. Still more detailed quantification is needed to evaluate the impact of this opposite observation especially in relation to coastal evolution.

Another very complex depositional environment is the area east of Zeebrugge (Figure 17). Field experiments have intensively been carried out in the framework of the extension works of the harbour, dredging activities and related to beach and foreshore dynamics. Most recently, very detailed sediment transport measurements were carried out in the MOBAG2000 framework. On the basis of state-of-the-art techniques, very-high suspended sediment transport values were measured near the dumpsite of dredged material and this in a NE or flood-dominated direction. BLOMME et al. (1994) demonstrated the high spatial variability of the amount of sediment transport on the one hand due to the sheltering effect of the harbour jetties, but on the other hand very high values were modelled outside the influence zone. The MU-SEDIM model results indicate a convergent sediment transport in this area and witnesses the importance of the outflow dynamics of the Westerschelde estuary. Interestingly, CHARLET (2001) also put forward a convergent sediment transport (albeit shifting in time) based on the shape and asymmetries of a field of large dunes, northward of the Paardenmarkt shoal. From this, it can be concluded that in order to obtain a good quantification of sediment transport, a larger sedimentary environment should be considered here. Moreover, as a first estimate of the complexity involved, an analysis of the bedforms can be recommended. If available, numerical sediment transport models provide results on a larger area and can be used as a first approximation of the sediment transport.

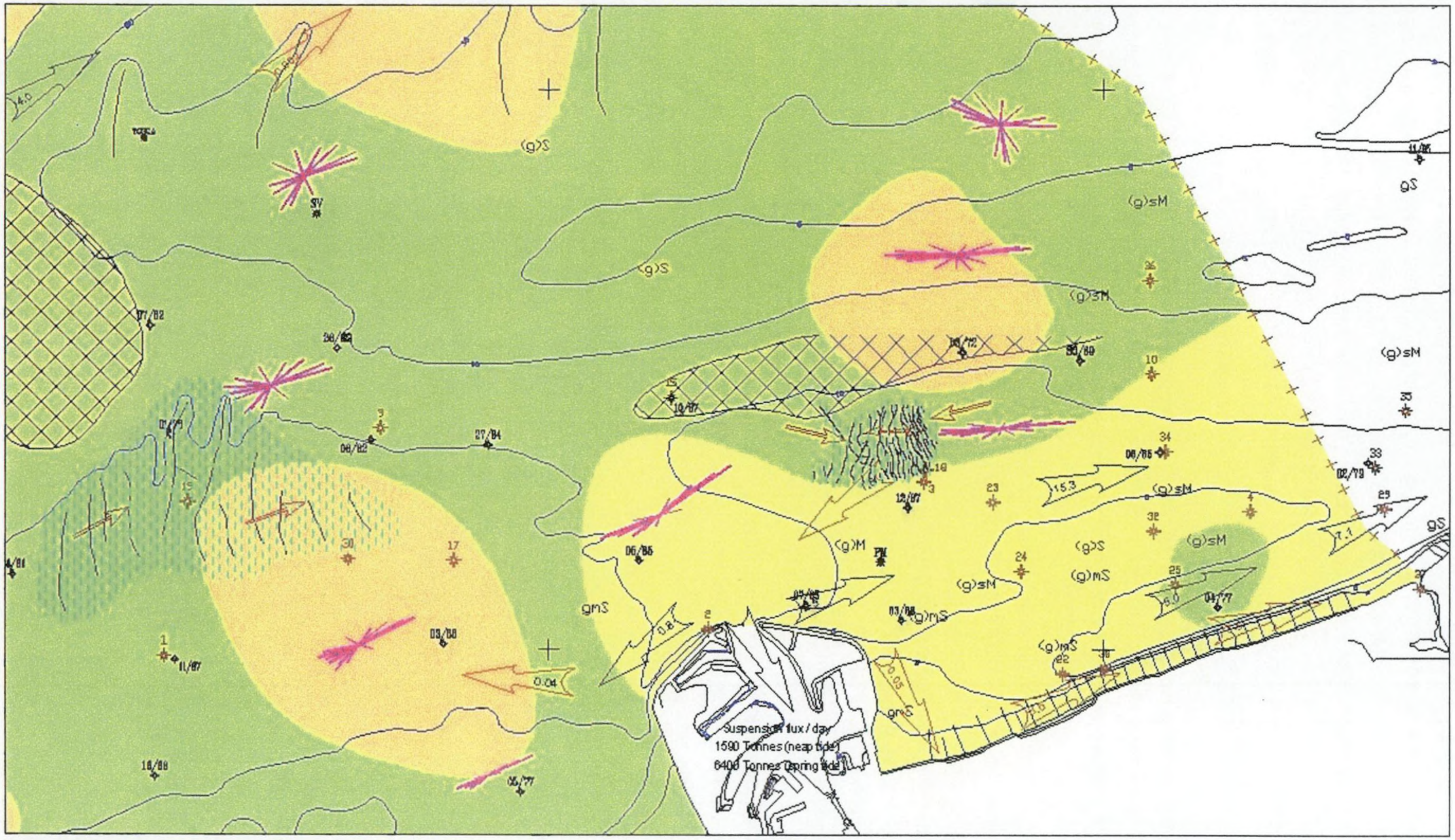

Figure 17. Synthesis of the sediment dynamics in the area east of Zeebrugge (Legend see Synthesis Map, Annex 2).

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions and gaps in the knowledge

The compilation map of the BUDGET project reveals the large amount of sedimentological, morphological, geological and sediment dynamic data available on the BCS. Due to its small size, the overall BCS has been generally well studied and even time-series of bathymetric, hydrographic and sedimentological measurements are available for a number of locations.

However, a closer look at the distribution of data points shows that most of the research has been carried out in a narrow coastal section over a width of ± 8 km. Furthermore the development of the new outer harbour of Zeebrugge has generated a large amount of sediment dynamic studies and as such much more results are available for the East coast compared to the West coast. More offshore, the sandbanks under extraction (mainly Kwinte Bank and Goote Bank) have been the subjects of a monitoring programme. Very little research was carried out on the remaining sandbanks and generally it can be stated that the amount of research on a particular site offshore is inversely proportional to the distance from the coast. This means that few studies concentrated on far offshore locations such as the Hinder Banks.

Future research will have to focus in some particular locations and fields of interest in order to find satisfactory answers to some of the questions that remain unsolved.

From the data available and its critical analysis, some conclusions can be drawn regarding the main bedload transport pathways on the BCS. Regarding bedload, bedforms remain the most important indicators. It has been shown that a distinction should be made between local and regional transport pathways. On a sandbank level, both bank flanks are subdued to opposite sand streams with a convergence to their crest line and even a circulation of sand has been postulated which was confirmed both by tracers as modelling studies. On a regional scale, and from offshore to onshore, it has been outlined that bedload transport is mainly to the SW in the Hinder Banks region, in the swales of the Flemish Banks and near the Goote Bank. Closer to the coast, the situation becomes somewhat ambiguous. From current modelling, the coastal zone is clearly flood dominated though the shape of the bedforms tends to reflect a dominant influence of the ebb tidal current and their asymmetry is often nearly symmetrical. This is especially clear near the French – Belgian border where complex bedload pathways are found even in the swales that strongly funnel the flood current. Also east of Zeebrugge bedforms reflect an alternance of flood and ebb dominant episodes, likely related to the ruling hydro-meteorological conditions. Although based on total load transport formulae, the model mu-SEDIM developed in the framework of this project, gives a first good indication of the likely pathways on the scale of the BCS.

The project did not focus on the processes that cause sediment transport as this is beyond the scope of this synthesis study. However, clear examples have been provided on the influence of external factors. It has been outlined that a quantitative relation can be found between varying hydro-meteorological conditions and sedimentation/erosion patterns. As such an analysis provides insight into the vulnerability of a coastal system, it is highly recommended to choose optimal sites to test this correlation and preferentially, these sites can be part of ongoing monitoring studies. It is thought that these areas are preferentially bedload convergence locations as these reflect a larger scale sediment dynamics.

The correlation with varying hydro-meteorological conditions can also help in improving the knowledge on the time scales involved in sediment transport processes. Moreover, for each important region, the ratio of the impact of storms or short-term events to long-term fair weather conditions should be investigated.

A challenge remains the set-up of a realistic sediment budget for the entire BCS. Theoretical estimates of the residual sediment fluxes have been presented, but they are all based on substantial simplified models. Input parameters are averaged values of water flux, residual current, depth section and surface sediment concentrations and the origin of some starting assumptions, put forward by some authors, is sometimes hard to find out and leads often to conflicting results.

On the compilation map, different values for residual suspension transport are given, mostly restricted to the near coastal zone. These values, obtained with different techniques, are in the same order of magnitude. However, realistic quantification of the residual transport, based on extensive field measurements, is only available east of Zeebrugge, over a width of +/- 5 km. The existing figures such as the ones offshore Knokke cannot be extrapolated as the suspension values near the coast are all extremely high and the values decrease substantially in an offshore direction. This is an important gap in the knowledge on the sediment fluxes across the BCS and a meaningful estimation can only be obtained if extra measurements are carried out along the borders. Moreover, more research is needed on the influence of the outflow of the Westerschelde estuary on the dynamics of the coastal zone including the Flemish Banks region.

A quantification of sand transport coming from the north and integration with data from the English and Dutch shelf seems a necessity to understand the sand transport on the BCS. No direct measurements have been made on the input of sand from the French shelf. Bedform evidence and sedimentological differentiation tend to indicate a significant input whereby the swales are the likely conduits of sediment transport.

5.2. Recommendations

5.2.1. Recommendations towards an integrated research strategy on the BCS

Introduction

A variety of new tools have been developed in the last decade. Some of them have already proven their efficiency in characterising the seabed, whilst others are still under continuous improvement. Some of these tools are highly relevant and applicable to the Belgian continental shelf and therefore it is recommended that Belgian research teams evaluate and use these techniques and compare their findings with results from other researchers who already applied them. The instrumentation that is listed below is definitely not exhaustive, but has been selected because of its relevance and the likely availability to Belgian research institutions.

Generally, emphasis is put on an efficient mapping of the seabed as such data is highly relevant for as well the research community as end-users. Moreover, samples are being taken for a variety of reasons, however mostly without taking into account the larger scale sedimentary environment. Especially towards monitoring studies and the study of temporal variations, it is highly advisable to select areas that are at least homogeneous over an area confined within the positioning error radius around sampling locations.

Mapping of the seafloor prior to sampling also enables to draw realistic maps of the seabed sediments distribution without a broad interpolation between individual sampling points. This is no criticism for past work as 10 years ago there was no alternative for this procedure. Today however better alternatives exist and should therefore be used especially if the end result is to be used for the production of maps with a large dissemination or to be used as a basic tool for decisions on management of coastal resources.

Mapping techniques

For a detailed and efficient mapping of the seabed, two measuring techniques are recommended:

Multibeam echosounder

- The multibeam echosounder has evolved from a complex tool reserved for highly specialised teams of engineers to a user-friendly technique available to all researchers, albeit with a basic training in system operation and data processing. The research vessel 'Belgica' is now equipped with a Simrad EM1002 multibeam system. Although the Ministry of Economic Affairs acquired the system, research institutions can be apply for its use.
- The multibeam echosounder installed on the 'Belgica' is a tool that can be used both for morphological and sedimentological studies. A multibeam system does not measure the water depth in a vertical plane under the transducer (as a single beam instrument does) but also performs measurements across track over a width of 7 to 8 times the water depth ("swath"). If during a multibeam survey the track interval is chosen in such a way that the outer beams of the 2 adjacent tracks overlap, depth measurements can be obtained from the entire area (e.g. one sounding per m^2 of the seabed) allowing an accurate mapping of the seabed topography including the geometric characteristics (such as crest line and slope) of all detectable bedforms.
- The advantage in using the multibeam of the 'Belgica', lies in the fact that the received acoustic echoes contain as well information on the nature of the seafloor itself. A software package, called Triton (Simrad), makes a classification of the seabed sediments possible by analysing the backscatter intensities of each beam. A number of statistical features are extracted from the backscatter values and used in the classification of the sediments in a number of predefined sediment classes. The use of this relatively new software has been initiated by the Marine Sand Fund Group of the Ministry of Economic Affairs and has proven its efficiency. As the multibeam system is calibrated, backscatter values can be compared from one area to another (and even from one instrument to another) and hence different groups can work towards an overall sediment classification scheme on a common ground.

  A reconnaissance survey was carried out in the Hinder Banks region using multibeam technology. Calibrated with limited samplings and complementary to the work of the Marine Sand Fund, the Triton software was applied and led to a first acoustical characterisation of coarse mixed sediments (DELEU 2001).

Digital side-scan sonar

Side-scan sonar has been used since several decades to map the seabed. While the interpretation of the recordings on paper rolls was rather time consuming and liable to inaccuracies (the image was not scale corrected and all measurements had to be mathematically transformed in function of a number of parameters such as the ship's velocity and the slant range), the development of new digital techniques and advanced software nowadays enable to obtain a fully corrected and geo-referenced image. These images can be produced at any scale according to any geodetic datum or projection. Moreover, a complete, full-coverage, image of the seabed can be obtained if the track interval is chosen in such a way to allow an overlap of the images between adjacent lines.

As the side-scan sonar is as well an acoustic technique, the backscatter values can be used to carry out a sediment classification. By making use of image texture analysis, an automatic classification of seabed types can be performed.

The benefit of the use of digital side-scan sonar imagery has been demonstrated throughout the OSTC-HABITAT project. Figure 18 displays a section of a side-scan sonar mosaic in which differences in backscatter values, linked to differences in sediment composition and density are clearly visible.

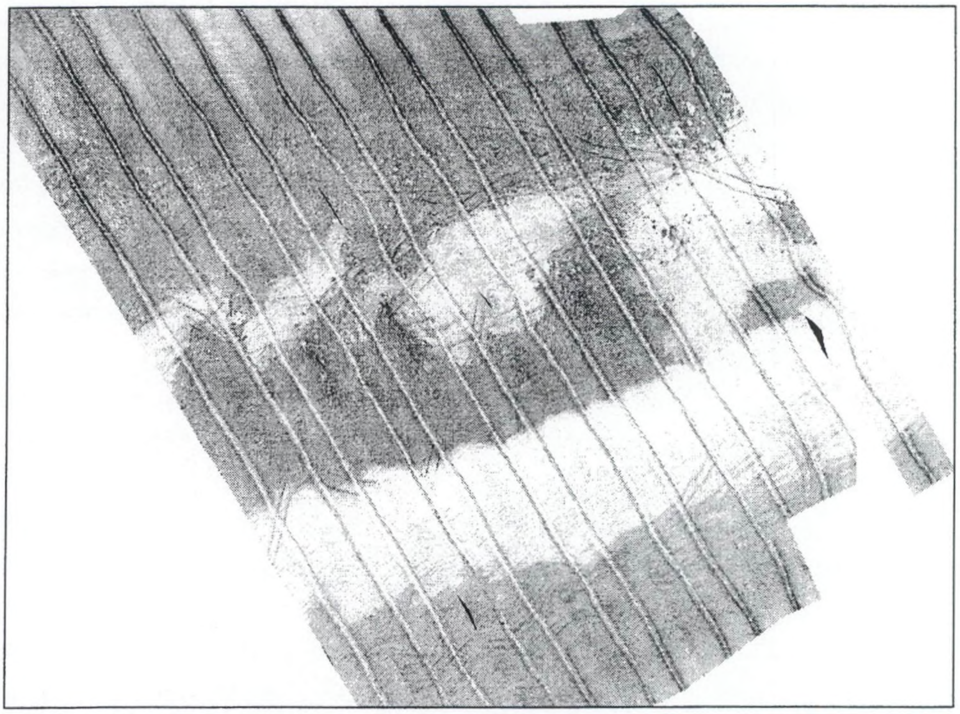

Figure 18. Section of a side-scan sonar mosaic recorded in the framework of the OSTC HABITAT project. Differences in backscatter correspond with differences in sediment composition. The lightest reflectivity was correlated with the presence of fluid mud intersected with trawl marks (double lines).

Conclusion mapping techniques

At first sight side-scan sonar and multibeam echo sounder could be considered as two techniques that produce similar results concerning information on the bedforms and on the sediment nature of the seabed. However there are some fundamental differences between both techniques:

There are three major advantages to the digital side-scan sonar compared to the multibeam:

- Its resolution is much higher what makes the system ideal for the analysis of smaller features, bedforms and small-scale patterns such as produced by some benthic communities;
- Its swath width is independent of the water depth what makes the system much more suitable for shallow water;
- The system is more portable and can be used from any vessel of opportunity.

A multibeam system however has two major merits:

- The system produces quantitative depth information what makes the system ideal to assess changes in depth and volume;
- The seabed classification is based on calibrated values that make all results interchangeable. The software for seabed classification based on side-scan sonar results, does not allow (for the moment) this possibility.

From this, it can be deduced that both techniques are complementary and therefore a simultaneous use is recommended for any large mapping project. In May 2001, the BUDGET team successfully demonstrated the feasibility of such a combined use including simultaneous seismic data acquisition.

Regarding the automated characterisation of seabed sediments, other techniques exist. An example is a gamma-ray detector system (a.o. MEDUSA 'Multiple Element Detector System for Underwater Sediment Activity') which is mostly used for the mapping of sand and mud (i.e. VAN WIJNGAARDEN et al. (2001a); VAN WIJNGAARDEN et al. (2001b)). The detector is towed over the seabed and registers differences in activity concentrations of the $_{238}$U- and $_{232}$Th-series and of $_{40}$K in sand and mud. After calibration with *in-situ* measurements of the natural radioactivity on the sea floor in combination with detailed sample analysis, the radiometric characteristics of sediment groups can be determined. Subsequently, the radiometric data that is acquired with the towed system can be translated into sediment maps. The use of such a system (MEDUSA) has been illustrated during a methodological workshop organised in the framework of the BUDGET project (March, 8th 2001). Examples were shown in the framework of monitoring dispersal of sludge dumped at sea (VENEMA et al. 1999).

Advanced groundtruthing techniques

It has been demonstrated that multibeam and/or digital side-scan sonar are efficient tools for large-scale seabed mapping purposes. However, groundtruthing remains a necessity especially since more research is needed regarding the true correlation of acoustic means and sediment characteristics.

To accomplish this aim, it is recommended to perform a groundtruthing in all areas showing a particular acoustic signature. However, such a validation should not only be based on grab sampling as this technique does not always reveal all information that influences the backscatter values. A thin veneer of mud for example could easily be destroyed by taking a grab sample. To obtain more information over which part of the seabed the backscatter values should be evaluated, the use of shallow boxcores seems to be highly valuable as a first approach.

Towards the characterisation of coarse mixed sediments, an efficient sampling remains problematic. This is mainly due to the lack of quantitative sampling devices that avoid a wash out of sediments. However, as the localisation of coarser sediments becomes more important (MAERTENS (2001)), it is advisable to consider the use of a suitable sampling device. An example is the Hamon grab, which is recommended as an industry standard tool for marine aggregate prospecting (a.o. UK, The Netherlands). Ideally, these devices are combined with video imagery.

The use of a sediment profile imager (SPI) was tested on the Belgian continental shelf (SGEG, Ghent University). This technique provides images of sea bottom profiles through the insertion of a wedge-shaped object with a plexiglass face plate through which camera images of sediment and water can be taken up to a depth of ca 25 cm. The recorded images normally allow visual and digital inspection of the sediment properties and sea bottom activities. Unfortunately, a poor penetration prevented a good evaluation of the technique and the high turbidity in the water column did not allow obtaining images of the seafloor surface.

Another similar, promising tool is the use of a benthic towed sledge which cuts through the upper twenty centimetres of sediment providing a cross-sectional real-time digital video sequence of sediment properties (like the "Plowscan" produced by Sea Sense). The sub-surface sediments are viewed with a mirror box in a similar way to the SPI technique. The system can be equipped with an additional video camera to view the seabed from above and other self-recording instruments such as OBS turbidity sensors.

Generally, photographs or video imagery of the seabed remain extremely useful for the characterisation of the seabed. Not only does it help in the validation and groundtruthing of acoustic means, but also it has broad applications towards biodiversity studies. In that sense, their use is often regarded as a standard procedure for mapping projects. Since, the sampling of the seabed itself remains of utmost importance, it is recommended to evaluate the implementation of such imagery on a variety of sampling devices. The images can also be taken with the help of small ROV's (Remotely Operated Vehicle). However, their use could be slightly problematic as the available Belgian research vessels are not equipped with dynamic positioning systems, which is highly advisable in waters with strong tidal currents.

Hydrodynamical and sediment transport measurements

Hydrodynamical and sediment transport measurements remain of vital importance for any sediment transport study. Although, a mathematical model may be the most suitable technique for calculating the effect of long-term and large-scale sediment transport processes, it is a necessity to feed the models with realistic data on current speed and sediment concentration data. Moreover, quantification of sediment transport and its translation towards sediment budgets remain important towards a sustainable management of the seabed. Nowadays instrumentation allows the set-up of integrated measuring campaigns including as well hydrodynamic as sediment transport related data acquisition.

Especially, towards sand transport studies, multi-sensor bottom-mounted frames should be used that are deployed over at least a sping-neap tidal cycle. These allow to obtain data related to bedload and suspended load processes whereby the height of the sensors above the seafloor is adjusted according to the objectives. Although, this configuration allows to obtain detailed information on seabed dynamics, they remain point observations and extrapolation to a larger scale is often difficult.

The suspended sediment concentration is in most cases still measured by taking water samples albeit mostly in combination with one-parameter sensors such as an optical transmission sensor, an optical backscatter sensor or an acoustic cross section scattering sensor. A one-parameter sensor obtains a weighted sum of the concentration of underlying size classes and for this reason the calibration of the sensors is a crucial step.

Calibrating the sensor in a laboratory may be of limited value if the particle size distribution in the water is variable (as is probably the case on the BCS). Optical transmission or backscatter sensors estimate the total particle cross-sectional area. Acoustic backscatter sensors (ABS) operating in the Rayleigh regime (i.e. ensonifying acoustic wavelength of the same order or greater than the particle diameter) respond to the sum of the squares of particle volumes. The measurement of the dynamic range of particles using ABS requires thus multifrequency acoustic sensors with the disadvantage that there exists a mismatch between the size range and the ability to reproduce small acoustic wavelength needed to measure fine particles. Acoustic sensors are therefore often used to measure the sediment concentration in the bottom boundary layer.

A promising technique for the acquisition of current meter data is the acoustic doppler current profiling sensor, which measures the current speed and direction by determining the scattered acoustic signal reflected by particulate matter in the water column together with the Doppler effect. Acoustic doppler current profilers (AcDCP) are widely used and have proven their efficiency. Generally, the instrument can operate from a bottom-mounted frame, deployed from a vessel or other platforms or rigidly mounted. The latter configuration allows obtaining real-time vertical current profiles whilst sailing.

The instrument can also provide information about the quantity of suspended matter. This information is obtained from the intensity of the reflected signals also referred to as the backscattering strength or signal amplitude. Using acoustic backscatter signals from an ADP type of instrument also requires careful calibration in order to transform correctly the backscattering strength data to concentrations of particulate matter. Hence, additional measurements (water samples, one or several optical backscatter sensors) are an essential part of the experiment making the measurements technically difficult. When using other sensors for calibrating the ADP (e.g. OBS, which has also to be calibrated) one must be aware of the fact that both instruments respond differently to the suspension in the water column. Ideally, both types of instrumentation are deployed simultaneously, over a period covering a neap to spring tidal cycle and preferentially under a variety of hydro-meteorological conditions. This measuring system will allow obtaining current and turbidity data over the entire water column.

An instrument that offers the capability to observe a wider range of particles and with potential towards sediment transport quantification is a laser in-situ scattering and transmissometer (LISST). The LISST-100 laser in-situ particle sizer measures volume concentrations by emitting a laser beam into the water with a conversion towards particle size spectra. The particles (flocs and aggregates if present) in the water cause the laser beam to scatter, creating a scattering pattern (AGRAWAL and POTTSMITH (2000)). In order to get mass concentration, the measured volume concentration data have to be calibrated by multiplying them with the density of the flocs or particles. The diffraction pattern is related to the flocs or aggregates themselves, rather than to the primary particles and/or microflocs (MIKKELSEN and PEJRUP (2001)). The LISST-100 instrument allows gaining insight into the size-dependent sediment transport processes, the relation between the current stress and the mean sediment size and the settling velocity of the flocculated matter (MIKKELSEN and

PEJRUP (2001)). The size-distribution of the local sediments plays a key role in controlling the suspended sediment size dynamics. This type of instrument is relatively new and promising and has up to now not been used for research purposes on the BCS. It can also be mounted on a bottom frame and deployed over a longer time period.

Numerical modelling

The sediment dynamic related field measurements (including bathymetrical, current and wave measurements, concentration and density profiles) can be used as input, calibration and validation of numerical modelling. Nowadays software allows 2D depth-average or 3D hydrodynamical modelling of the current and water transport as well due to tidal as to different hydro-meteorological conditions. Moreover, the propagation and transformation of waves can be simulated including the evolution of waves for a variety of wind stresses, current velocities and water depths.

Apart from calculations regarding residual sediment transport, the effects of waves, currents and sediment transport can be integrated to simulate the morphological evolution of the seafloor over time-scales of days to years including their complex interaction and the resulting seafloor adjustments. The sediment transport calculations can include bedload, suspended and total load transport (bedload + suspended load) under the influence of the current, waves and current-wave interaction.

Existing models are the in-house developed BCS hydrodynamic model and the Coherens model of MUMM that can be refined according to the complexity of areas and/or the needs of the end-user (grid resolution up to 250 m or less and 2D or 3D) (e.g. OZER et al. (2000)). VAN DEN EYNDE (1998) developed a sediment transport model for the Belgian coast. A coastal zone model using DELFT3D software has been developed at the Flanders Hydraulics Institute (HAECON (1999)). The latter enabled a nesting of a more detailed model of the Belgian East Coast (DE WIT 2001). The resolution of the grid is about 50 m x 50 m near the coast up to 100 m x 700 m towards the offshore. Apart from current modelling, also waves were taken into account based on the SWAN model (Simulating Waves Nearshore) and the current-wave interaction.

Seabed mobility studies

An example of the application of an integrated research strategy is a seabed mobility study. Within the spirit of the BUDGET project, such a study was carried out in the Hinder Banks region, abeit in its restricted form. The Hinder Banks area was chosen as only limited data was previously available often leading to a blank area on maps. By means of newly acquired multibeam/single-beam data and limited samplings, a reconnaissance survey was carried out. Further processing of the multibeam data towards automated seabed classification led to a first acoustical statistical characterisation of coarse mixed sediments. The compilation of newly gathered and existing data in combination with existing numerical model results allowed to evaluate the sediment transport capacity in the area and shed new light on sediment provenance areas (DELEU 2001).

This kind of study can be largely upgraded according to the techniques and instruments available. Ideally, currents and waves and their interaction are taken into account based on in-situ data. This would allow studying the current-topography interactions in more detail and this under a variety of conditions.

5.2.2. Recommendations towards a sustainable management of seabed resources

A large amount of sediment dynamic research has been carried out on the BCS in the last decades as well in the framework of national and international projects (for an overview, see Annex 1). The density of data available is however largely constraint to areas of special interest such as related to the implementation of large infrastructure or the concession zones for marine aggregate extraction. For other sections simple, basic parameters (e.g. mean grain-size of the surficial sediment) are extremely difficult to find although they are of great interest to a large amount of end-users.

The compilation of the available data was upgraded through the set-up of a synthesis map essentially integrating the sedimentological, bathymetrical and morphological nature of the seabed added with a sediment dynamical interpretation and net sand transport directions.

However, the scale of the map (1/100.000) made it impossible to represent essential details such as individual crest lines of large bedforms or grain-size variations, even on the scale of a sandbank. Still, on certain sections of the BCS, those data exist and would enable to produce more detailed sedimentological, morphological or combined maps.

Thematic maps have been produced for different French coastal areas in the framework of agreements between the "Régions" and Ifremer. One of these maps covers the section of the continental shelf between Calais and Duinkerke, but ends at the French-Belgian border. Recently, a large-scale mapping project (Geosynth) was set-up by the French and British Geological Surveys, the French Hydrographic Office (SHOM), IFREMER and the University of Lille, however without Belgian partnership. In the framework of the BUDGET final workshop, the strategy and some results of the Geosynth project were presented. Especially, on a seabed resource mapping level, it would be highly advisable to evaluate to what extend the BUDGET and Geosynth project results can be merged and what steps this would require.

To enhance the efficiency and practical use of seabed data, the set-up of an overall *Geographical Information System* (GIS) on the available marine aggregates becomes timely and would enable to select data according to end-users' needs. However, caution is needed if contour maps are automatically generated without prior knowledge on the sedimentary environment and if specific derivatives are needed.

Moreover, it is recommended to set-up guidelines and protocols on the prerequisites of mapping and sampling projects since this would largely facilitate the set-up and evaluation of environmental impact assessments (EIA). If indeed a GIS on the BCS seabed would exist, it could provide standardised background information. In any case, an overall data management seems inherent to efficiently anticipate on future needs and to facilitate the decision-making.

6. SYNTHESIS

Characterisation of the Belgian continental shelf (BCS)

The Belgian continental shelf (BCS) is characterised by a number of sandbanks that can be grouped as Coastal Banks, Flemish Banks, Hinder Banks and the Zeeland Ridges. The Coastal Banks and the Zeeland Ridges are quasi parallel to the coastline, whilst the Flemish and Hinder Banks have a clear offset in relation to the coast.

From a geological point of view, it has been shown that at least some sandbanks are not merely an up-piling of sand, but a result of different well-distinct evolutionary phases. Subsequently, the sediments involved can be very diverse in nature and vary from clay to coarse sands and gravel. However, only the upper sediment cover is representative of the present hydrodynamic regime. It was deduced that the thickness of the Quaternary is less than 2.5 m in most of the swales of the BCS with locally erosion of Tertiary clay deposits can occur.

The morpho-sedimentological characterisation of the BCS included the compilation of morphological and sedimentological data in order to give evidence of areas with a high sediment transport potential. To accomplish this aim emphasis was put on the occurrence of larger bedforms as they are formed under a higher current regime and are usually associated with areas having a significant sediment input. In this framework it was also important to know the sediments involved and hence a compilation of sedimentological data was a necessity.

To present a global overview of the presence and characteristics of the bedforms on the BCS, the occurrence of large dunes (sandwaves) were mapped based on information from publications, side-scan sonar surveys and single- and multibeam registrations. If sufficient dimensional data was available, fields of height classes were visualised.

Generally, the highest dunes are observed at the northern extremity of the Flemish Banks (up to 8 m) and in the northern part of the Hinder Banks region. Higher dunes are also observed at kinks that are often observed along sandbanks. Fields of large dunes also occur at the western extremity of the Goote Bank and in the northern part of the Hinder Banks region where they were abundantly observed in the swales. Closer to the coast their occurrence is merely restricted and the sandbanks are generally devoid of bedforms. Remarkably, the highest dunes are sometimes found in the shallowest areas.

On a sedimentological level, the nature and differentiation of the surficial sediments is mostly related to the unique configuration of the sandbank-swale systems whereby the interaction of the current with the large-scale morphology is responsible of a hydraulic sorting of the sediments. The sand fraction (0.063 to 2 mm) preferentially takes part in the up-building process of the sandbanks whilst the coarser sands, gravel (> 2mm) and the silt-clay fraction (<0.063 mm) are merely found in the swales. The general coarseness of the steep slope of the sandbanks is due to the erosive action of the flood tidal current along this slope. The gravely deposits in the swales are merely relict sediments that are hardly moved by the present hydrodynamic regime and therefore it should be evaluated whether they are a renewable sediment source or not. Generally, the finest sediments can only deposit in the deeper swales, but studies in the near coastal area showed that muddy deposits can occur up to a depth of – 6 m MLLWS if a high availability of fine suspended matter exists. Shallower, this fraction is washed out by an interplay of currents and waves. On the scale of the BCS, the surficial sediments generally coarsen in an offshore direction. A literature overview is given of the existing sedimentological studies and this on as well a large- as on a small-scale basis.

The availability of current and other hydrodynamic measurements carried out on the BCS is discussed. However, most hydrodynamical measurements are rather short-term and are related to specific research questions. The model relevant for the understanding of the current propagation on the scale of the whole BCS is implemented on a rectilinear grid and has a resolution of about 750 m x 750 m. Along the open boundaries, the model uses the output from the mu-STORM model, a 2D operational hydrodynamic model covering the North Sea and the English Channel. At the mouth of the Westerschelde, the model is coupled to a 1D hydrodynamic model of the Schelde estuary.

On a synthesis map the above mentioned information has been compiled. A selection is made of current ellipses typically for a spring tide calculated from the 2D hydrodynamic numerical model mu-BCZ. Noteworthy, are the strongly rectilinear ellipses in the near coastal zone and in the mouth of the Westerschelde. Offshore and on the Vlakte van de Raan, the ellipses are more rotary in nature with a veering towards the sandbanks. At the northern limit of the BCS, the current ellipses are again more rectilinear.

<u>Overview of sediment transport studies related to the BCS</u>

An inventory was made of all sediment transport studies related to the BCS both related to bed-load as to suspension load transport. For each study a summary is presented including information on (i) the method used to derive the sediment transport information, (ii) the principal results and (iii) the directions and quantities of the sediment transport that were deduced. The studies were classified according to the principal technique that was applied.

<u>Critical anlysis of the data and the methods used</u>

All results related to sediment transport were compiled and analysed per method.

Residual transport directions based on the asymmetry of bedforms.
The asymmetry of flow-transverse bedforms can be used to derive the residual sediment transport directions. Both small to medium dunes (megaripples) and large to very large dunes (sandwaves) have been used as transport indicators on the BCS. The asymmetry of the bedforms is in the first place defined by the dominant tidal current as the overall shape represents a state of quasi-equilibrium to the relative strength of the opposing flows. On a large number of sandbanks such as the Flemish Banks and the Hinder Banks the residual flood current shapes the bedforms on the western bank flank and the eastern part of the swale whilst residual ebb currents are responsible for the ebb-asymmetry of the bedforms on the eastern bank flank and the western part of the swales. This mechanism is responsible for a convergence of sand streams towards the bank's crest resulting in sand up piling on the bank's summit.

➢ The direction of the steep side of bedforms remains recommended to derive sediment transport directions. The results that were compiled from different studies are consistent and coincide with results derived from other methods. However the results of a single moment do not always show the residual transport directions on a large time scale as time-series of measurements have shown that nearly all large and small dunes can change their asymmetry and present an ebb-asymmetry or a flood-asymmetry. This alteration of asymmetry is caused by the effect of hydro-meteorological conditions whereby dominant wind and swell from a particular direction can amplify the flood or the ebb current. The speed of this adaptation to the net transport direction is function of the size of the bedform. Once the storm is over, the bedforms will return to their original tidal-induced asymmetry, but again the speed of this change will depend on their size. This means that bedforms can be used to derive the residual transport directions on a large time scale but in this case the effects of external factors have to be filtered out. The asymmetry of very large dunes (with heights of more than 8 m) can be considered as permanent and could therefore be used to deduce residual transport on a time scale of several years. Small dunes can also be used as transport indicators, however their vulnerability should be evaluated to the ruling hydro-meteorological conditions.

Residual transport directions based on tracer experiments.

A number of tracer experiments were carried out on the BCS and adjacent beaches. Three techniques have been used to study the residual bedload sediment transport.

- Radioactive tracers were used in the vicinity of the harbour of Zeebrugge and most results reflected the dominance of the flood current in the direction of the Dutch border. Coastward transport was mainly the result of wave action coupled to stormy weather conditions. North of Zeebrugge, a small residual transport was found in the ebb direction. A tracer experiment carried out on the Westdyck sandbank (France) indicated a NE residual bedload transport towards the Flemish Banks.

- Fluorescent tracer experiments were carried out on the beaches, eastward of Zeebrugge and of Nieuwpoort and indicated an eastward-directed residual transport. Only one fluorescent tracer experiment was carried out offshore. During this experiment, 2 deployments of fluorescent sand were made on both bank flanks of the Middelkerke Bank. The results, although biased and hampered by unfavourable weather conditions, showed that the sediment was moved residually in a NE direction on the western flank and in a SW direction on the eastern flank. Sediment movement around the bank in a clockwise direction could as well be deduced.

- Only one experiment with magnetically enhanced sand was carried out on the beach of Nieuwpoort. The results showed that the majority of the mobilised tracer material was transported in a SW direction.

A number of tracer experiments were carried out to assess the suspension load transport.

- Six injections of radioactive tracers were carried out. The results pointed to a re-circulation towards the coastal area where the sediment seemed to be trapped though with a slight dominance of a residual transport in a NE direction. Still, care is needed as a number of factors biased the conclusions.

- A number of natural tracers can be used to trace large-scale and long-term residual water movements. Measurements of salinity carried out on the Dutch shelf showed that the water travels residually in a NNE direction and that the movement increased from almost zero near the Belgian coast to about 6 cm/s near the Isle of Texel. Residual sediment movement can as well be deduced from the displacement of a suspended matter minimum and from the superficial water temperature detected on thermal infrared imagery.

The results of the tracer experiments carried out on the BCS have revealed useful information on the residual transport directions. The technique is however not always successful as certain factors can prevent a normal dispersion of the tracer particles. If the area in which the experiments takes place is subject to a sediment accretion the tracer substance can be covered with sediment which makes it unavailable for transport. Fluorescent tracer experiments in the offshore have to rely on extensive sampling operations making the method rather expensive. In this case other tracer methods, in which the detection of the marked particles can take place directly on the seabed by using a detection unit mounted on a sledge, should be favoured. As radioactive tracers are no longer in use due their environmental-unfriendly image, magnetic tracers could be considered for this type of research.

Residual transport directions based on sediment differentiation.
Variations in the areal pattern of grain-size parameters have been used in different ways to determine the residual sediment transport directions. Two techniques have been used on the BCS: Sediment Trend Analysis (STA) and fraction analysis.

- In the STA technique the coarseness, sorting and skewness of a sample is compared with its neighbours. Residual transport takes place if a specific transport trend can be defined between the two samples. Most studies carried out on the BCS agree that the most reliable results are obtained if a combination of the transport trends FB- (Finer, Better sorted, and more negative skewness) and CB+ (Coarser, Better sorted and more positive skewness) is used. Trends in which the sorting is worsening along the considered transport paths have little similarity with the transport trends from other methods.

- The STA technique was used on the entire southern North Sea, along the western and eastern near coastal area and on sections of the Kwinte Bank, Middelkerke Bank, Goote Bank, Ravelingen and east of Zeebrugge. An STA carried out on the whole southern North Sea showed that a distinction could be made between a coastal area in which transport vectors were pointed towards the coast and an offshore area in which a NE transport was dominant. The results of a STA carried out on the scale of a coastal system and on sections of sandbanks comply with the directions derived from bedform analysis. The sediment dynamic model deduced from the bedform asymmetry in which sand is moved residually on both bank flanks by the effect of flood and ebb currents, was in agreement with the results of the STA.

- From the results, it can be deduced that STA is suitable to gain insight into sediment transport directions. However to deduce *residual* transport directions, it should be compared and integrated with complementary techniques and some prior knowledge of the hydrodynamic environment will greatly help to understand the obtained results. It remains highly advisable to carry out an STA in an environment where hydrodynamical agents equally influence the surficial sediments as otherwise time constraints might strongly bias the results. Moreover, the most reliable results are expected if only one depositional environment is taken into account.

- The study of the distribution of the different grain-size classes individually can provide a better insight into the processes governing the physical functioning of a coastal system. This technique was applied in the western near coastal area where processes of coarsening, fining and winnowing of specific grain-size fractions could be observed and related to differing hydro-meteorological conditions. Relatively, the coarsest sediments were found under calm weather conditions whilst under rougher conditions finer sandy sediments can be brought into the system and deposited.

Residual transport directions based on current and suspended sediment concentration measurements

- A large number of current measurements and sediment concentration measurements were carried out on the BCS mainly in the framework of the construction of the new outer walls of Zeebrugge harbour. These short-term observations provide an insight in the order of magnitude of the suspended sediment, but they are subject to important fluctuations in time.

- Data on current speed and sediment concentrations over a long time (spring-neap cycle) are preferentially obtained through continuous measurements with the help of sensors such as Optical Backscatter Sensors (OBS) or Acoustic Doppler current Profiling sensors (ADP). Measurements can be made from a ship or by using bottom frames. A small number of these measurements have been carried out in the past. Measurements on the relocation grounds Zeebrugge East and S1 made it possible to assess accurately residual suspension transport rates and directions during spring (up to 15 tonnes/m/day), middle and neap tide (up to 4 tonnes/m/day).

- Sediment concentration measurements in combination with aeroplane multispectral scanner recordings and a 2D hydrodynamic model have been used to calculate the suspended sediment transport in the entire Belgian coastal zone. The residual transport was parallel to the coast and flood-dominated for nearly the entire coast. Residual transport values varied between 0.6 and 5 tonnes/m/day.

Residual transport directions based on sediment transport models

The numerical sediment transport models, which have been applied to the BCS can be divided in suspended load and in total load models.

- The cohesive sediment transport models of the BCS are regional 'engineering' type models containing many simplifications (due to the limited knowledge of the physical environment). The turbulence fields, parameterised as subscale phenomena, the bed composition and the boundary conditions are poorly known, due to a lack of field data bed dynamics (erosion and deposition as a function of sediment composition, transport, consolidation) are simulated using simplified relations, biological processes are ignored.

- The processes responsible for the high turbidity formation are the currents and the import of suspended particulate matter (SPM) through the Strait of Dover. Due to mainly the decreasing magnitude of residual transport, which is NE directed and the shallowness of the area, the SPM is concentrated in the Belgian-Dutch coastal waters and is forming a turbidity maximum in front of Zeebrugge. The occurrence of a high turbidity zone can best be compared to a kind of sediment congestion; it is an open sediment system. The erosion of Tertiary clay, Holocene mud and peat layers is partly responsible for the increase of the SPM concentration in the considered area.

- Fine grained sediments are continuously deposited and re-suspended showing variations during tidal cycles, neap-spring cycles and during changing meteorological conditions. Deposition, re-suspension and transport of mud during a tidal cycle are basic processes and are responsible for the magnitude of the SPM concentration in the turbidity maximum area.

- The difference in magnitude between spring and neap tidal currents is partly responsible for the fact that the mud deposits are permanent. Especially, during neap tide, the mud has a higher probability to build up a structure, to consolidate and to increase its erosion resistance. More mud is thus found on the bottom and the SPM concentration is relatively low. During spring tide the opposite happens and part of these deposits are again re-suspended.

- A recent total load model uses hydrodynamic and wave information to calculate the sediment transport. The results show a sediment transport on the sandbanks in a clockwise direction: to the NE on the W flank of the banks and SW directed on the E flank of the bank. In the coastal zone (20 km) the transport direction is towards the NE. In the Scheur the direction is towards the W. In open sea (north of the sand banks) the sediment transport direction is towards the SW.

Evaluation criteria

Time and spatial scales of the residual transport results obtained with different methods can be quite different so care is needed comparing results obtained with different techniques. All techniques applied on the BCS were classified according to the corresponding time and spatial scale. Four different categories were defined for both time (micro scale: hours to days; meso scale: days to weeks; macro scale: weeks to months; mega scale: years to decades) and spatial scale (micro scale: 0.1 to 1 m; meso scale: 1 to 100 m; macro scale: 100 m to 1 km; mega scale: 1 to 100 km).

Sediment budgeting

Using the existing data it is difficult to set up a quantitative sediment balance (sand fraction) of the BCS. Quantitative data exist however for the human activities on the BCS, such as the dredging works, the study of the dumping place B&W S1 and data on sand extraction and beach nourishment.

- Yearly about 1.4×10^6 t dry matter (TDM) of sand is dredged in the navigation channels
- Measurements indicate that 80-90% of the dumped sand stays on the dumping place. The results of a Sediment Trend Analysis (STA) suggest that the remaining 10-20% are transported back to the navigation channels. This corresponds to replenishment for the dredging year 1997 of 0.08-0.16 TDM (15-30%) from B&W S1. The same STA results indicate that the most important replenishment of the navigation channels is from sand transport from the west (Wenduine Bank, Wandelaar).
- Erosion occurs along some parts of the Belgian coast. During the nineties about 1.1×10^6 TDM/yr of sand have been extracted for beach nourishment works.

- Every year 2.5x10^6 TDM of sand is extracted (90% on the Kwinte Bank).
- From national and international investigations, a global transit of 5 x10^6 to 10x10^6 TDM/yr is estimated as being transported along the French, Belgian and Dutch coast in a NE direction. Recently, an estimate of 20x10^6 TDM/yr is reported for suspended matter, still this needs further investigation.

On the basis of a 40 days measuring period of suspended sand profiles and current meter data on the Middelkerke sandbank, the following sand transport rates were obtained:

- 0.9 tonnes/m/day (up to 0.3 m above the bed) along the steep slope; this was 10 times that of the southern end of the bank (0.05 tonnes/m/day); sand transport was up-slope at 25 degrees to the bank axis, in the direction of the major axis of the tidal ellipse;
- The transport on the steep slope was mainly in the size range of 100-140 μm which did not occur in any significant proportion in samples of the sea bed at that site leading to the conclusion that this fraction is likely advected from deeper water (SE);
- Excluding the finer component, the transport rates of coarser sand (>200 μm) at the two sites were similar over the 40 days period;
- The transport rates are consistent with a time-scale of 100-1000 yr for the formation of the bank.

Recommendations

Emphasis is put on an efficient mapping of the seabed as such data is highly relevant for as well the research community as end-users and this as well for small- as large-scale applications. Two mapping techniques are recommended: multibeam and side-scan sonar. Both techniques are complementary and in combination a very-high resolution quantitative mapping of the seafloor including its the intrinsic nature can be obtained. Furthermore, both allow to quantitatively process the backscatter data and through the set-up of automated classification schemes a tools is provided for an efficient mapping of seabed sediments. Still, other techniques exist and deserve further investigation and exploration.

Groundtruthing remains a necessity especially since more research is needed regarding the true correlation of acoustic means and sediment characteristics. Stratified sampling based on the different acoustic facies could allow to set-up groundtruthed seabed classes that ideally comprise the variety of aggregates found on the BCS. However, according to the sediments involved, appropriate sampling tools should be chosen, preferentially integrated with video imagery. This will also open up perspectives towards biodiversity studies.

Sampling operations should be efficiently planned and take into account the larger scale sedimentary environment. Especially towards monitoring studies and the study of temporal variations, it is highly advisable to select areas that are at least homogeneous over an area confined within the positioning error radius around sampling locations.

Hydrodynamical and sediment transport measurements remain of vital importance for any sediment transport study. Although, a mathematical model may be the most suitable technique for calculating the effect of long-term and large-scale sediment transport processes, it is a necessity to feed the models with realistic data on current speed and sediment concentration data. Moreover, quantification of sediment transport and its translation towards sediment budgets are important towards a sustainable management of the seabed.

Especially, towards sand transport studies, multi-sensor bottom-mounted frames should be used that are deployed over at least a sping-neap tidal cycle. These allow to obtain data related to bedload and suspended load processes whereby the height of the sensors above the seafloor is adjusted according to the objectives. Although, this configuration allows obtaining detailed information on seabed dynamics, they remain point observations and extrapolation to a larger scale is often difficult.

The use of an acoustic doppler current profiling combined with data from optical backscatter sensors (well-calibrated) allows to calculate sediment fluxes over the vertical water column and in profile mode whilst sailing. The disadvantage is that often those measurements do not reach the seafloor itself although knowledge on this layer is vital for sand transport studies. ADP's can also operate from a bottom-mounted frame.

An instrument that offers the capability to study the particle size of the suspended matter and with potential towards sediment transport quantification is a laser in-situ scattering and transmissometer (LISST). This type of instrument is relatively new and promising and has up to now not been used for research purposes on the BCS. The instrument can also be mounted on a frame and deployed for longer time periods.

The sediment dynamic related field measurements can be used as input, calibration and validation of numerical modelling. Nowadays software allows 2D depth-average or fine-grid 3D hydrodynamical modelling of the current and water transport as well due to tidal as to different hydro-meteo conditions. Moreover, the propagation and transformation of waves can be simulated including the evolution of waves for a variety of wind stresses, current velocities and water depths. In combination with sediment transport modelling (bedload, suspended and total load transport) the morphological evolution of the seafloor can be simulated over time-scales of days to years.

An example of the application of an integrated research strategy is a seabed mobility study. The compilation of newly gathered and existing data in combination with existing numerical modelling allows to evaluate the sediment transport capacity in an area and sheds new light on sediment provenance areas.

To enhance the efficiency and practical use of seabed data, the set-up of an overall *Geographical Information System* (GIS) on the available marine aggregates becomes timely and would enable to select data according to end-users' needs. However, caution is needed if contour maps are automatically generated without prior knowledge on the sedimentary environment and if specific derivatives are needed.

Moreover, it is recommended to set-up guidelines and protocols on the prerequisites of mapping and sampling projects since this would largely facilitate the set-up and evaluation of environmental impact assessments (EIA). If indeed a GIS on the BCS seabed would exist, it could provide standardised background information. It could also include numerical reference material to guide sediment budgeting studies. In any case, an overall data management seems inherent to efficiently anticipate on future needs and to facilitate the decision-making.

7. SYNTHESE

Karakterisatie van het Belgisch continentaal plat (BCP)

Het BCP wordt gekenmerkt door een aantal zandbanken die gegroepeerd worden in de Kustbanken, de Vlaamse Banken, de Hinder Banken en de Zeelandbanken. De Kustbanken en de Zeelandbanken zijn nagenoeg parallel aan de kustlijn dit in tegenstelling tot de Vlaamse en Hinder Banken waarvan de as van de zandbank een duidelijke hoek vertoont t.o.v. de kust.

Een aantal zandbanken vertonen een complexe geologische opbouw die het resultaat is van verschillende evolutiefasen. Dit heeft als gevolg dat de sedimenten een zeer verscheiden karakter hebben en kunnen variëren van klei tot grof zand en grind. Alleen de bovenste sedimentlaag echter is representatief voor het huidige hydrodynamisch regime. De dikte van het Quartair is minder dan 2.5 m in de meeste geulen waar eveneens locale erosie van de Tertiaire klei kan plaatsvinden.

De morfo-sedimentologische karakterisatie van het BCP omvat de compilatie van morfologische en sedimentologische gegevens teneinde zones te definiëren die in aanmerking komen voor een verhoogd sedimenttransport. Hiertoe werd vooral het voorkomen van de grotere bodemstructuren gekarteerd daar deze gevormd worden onder een sterker stromingsregime en deze normalerwijze geassocieerd worden met gebieden gekenmerkt door een significante sedimentinbreng. Hiervoor was het eveneens noodzakelijk om de betrokken sedimenten te kennen waardoor een compilatie van sedimentgegevens noodzakelijk was.

Teneinde een globaal overzicht voor te stellen van de aanwezige bodemstructuren op het BCP, werden de zandgolven gekarteerd op basis van gegevens uit publicaties, side-scan sonar registraties en multibeam data. Wanneer voldoende numerische informatie over de hoogte van de structuren aanwezig was, werden de zandgolven ingedeeld in een aantal hoogteklassen.

Algemeen gezien komen de hoogste zandgolven voor op het noordelijk uiteinde van de Vlaamse Banken (tot 8 m) en in het noordelijk deel van de Hinder Banken. Hoge zandgolven werden eveneens opgemerkt nabij de kinken die voorkomen bij een aantal zandbanken. Velden van hoge structuren komen eveneens voor in het westelijk uiteinde van de Gootebank en in het noordelijk deel van de Hinder Banken waar ze in grote mate in de geulen geobserveerd kunnen worden (tot 11 m). Dichter bij de kust is hun aanwezigheid sterk beperkt en over het algemeen komen geen structuren voor op de zandbanken. Opvallend is dat de hoogste zandgolven soms voorkomen in de ondiepste zones.

Op sedimentologisch vlak, is de differentiatie van de oppervlakkige sedimenten hoofdzakelijk het gevolg van de specifieke bank-geul configuratie waarbij de interactie tussen de stroming en de grootschalige morfologie verantwoordelijk is voor een hydraulische sortering van de sedimenten. Enerzijds is de zandfractie (0.063 - 2 mm) de hoofdbestanddeel voor de opbouw van de zandbanken en anderzijds komen de grovere zanden, grind (> 2 mm) en de silt-klei fractie (< 0.063 mm) vooral voor in de geulen. Vaak is de steile flank van een zandbank gekenmerkt door grovere zandfractie wat hoofdzakelijk het gevolg is van een erosieve werking van de sterkste stroming langsheen deze flank. De grindafzettingen in de geulen zijn restsedimenten die nagenoeg niet vervoerd worden door het huidige hydraulisch regime. De hernieuwbaarheid van deze sedimenten is dan ook een open vraag. De fijnste sedimenten bezinken hoofdzakelijk in de diepere delen van de geulen, maar studies in de kustnabije zone tonen aan dat slib kan voorkomen tot een diepte van -6 m GLLWS in het geval hoge concentraties van gesuspendeerde deeltjes voorkomen. Ondieper wordt deze fractie uitgewassen door het effect van golven en stromingen. Op het niveau van het BCP worden de oppervlakkige sedimenten grover zeewaarts. Een literatuuroverzicht wordt gegeven van de bestaande sedimentstudies uitgevoerd op kleine en grote schaal.

Een overzicht van de stroommetingen en andere hydrodynamische metingen uitgevoerd op het BCP wordt voorgesteld. Het grootste deel van de hydrodynamische metingen zijn echter metingen op korte termijn en houden verband met specifieke onderzoeksvragen. Het wiskundig stroommodel dat inzicht verschaft over de voortplanting van de stroming op BCP schaal is geïmplementeerd op een rechthoekig grid met gridinterval van 750 x 750 m. Langheen de open grenzen gebruikt het model de output van het mu-STORM model (een 2D hydrodynamisch model dat de Noordzee en het Kanaal omvat). Bij de monding van de Westerschelde wordt het model gekoppeld aan een 1D hydrodynamisch model van het Schelde estuarium.

De resultaten van het hierboven vermeld stroommodel werden gecompileerd op de synthesekaart waarbij een aantal stroomellipsen weergegeven worden voor een springtijsituatie. Opvallend zijn de sterk afgevlakte ellipsen in de kustnabije zone en nabij de monding van de Westerschelde. Meer zeewaarts en op de Vlakte van de Raan worden de ellipsen ronder met een ombuiging nabij de zandbanken. Naar het noorden toe van het BCP, worden de stroomellipsen terug rechtlijniger.

Overzicht van de sedimenttransportstudies uitgevoerd op het BCP

Een inventaris werd uitgevoerd van alle sedimenttransportstudies uitgevoerd op het BCP, en dit zowel voor het bodem- als voor het suspensietransport.. Een overzicht van iedere studie werd gemaakt met aandacht voor: (i) de toegepaste methode voor het afleiden van het sedimenttransport, (ii)) de belangrijkste resultaten en (iii) de richtingen van het sedimenttransport en, indien aanwezig, de hoeveelheden getransporteerd sediment. De studies werden geklasseerd in functie van de belangrijkste toegepaste methode.

Kritische analyse van gegevens en toegepaste methoden

Alle sedimenttransportresultaten werden gecompileerd en geanalyseerd per methode.

Residuele transportrichtingen gebaseerd op de asymmetrie van bodemstructuren

De asymmetrie van bodemstructuren die dwars op de stroomrichting voorkomen, kan gebruikt worden om de richtingen van het residueel bodemtransport af te leiden. Zowel kleine tot gemiddelde duinen (megaribbels) als grote tot heel grote duinen (zandgolven) werden gebruikt als transportindicatoren op het BCP. De asymmetrie van de bodemstructuren wordt in eerste instantie gedefinieerd door de dominante stroomrichting daar de algemene vorm een evenwichtstoestand voorstelt dat het resultaat is van de relatieve sterkte van de tegengestelde stroomrichtingen. Op een groot aantal zandbanken zoals de Vlaamse Banken en de Hinder Banken, is de residuele vloedstroom verantwoordelijk voor de vloedasymmetrie van de bodemstructuren op de westelijke bankflank en in het oostelijk deel van de geul en leidt de residuele ebstroom tot een ebasymmetrie op de oostelijke bankflank en in het westelijk deel van de geul. Dit mechanisme is verantwoordelijk voor een convergentie van zand naar de bankas toe wat leidt tot een sedimentophoping op de banktop.

- Het gebruik van de asymmetrie van bodemstructuren leidt tot goede resultaten om de richting van het residueel sedimenttransport af te leiden. De resultaten die gecompileerd werden van de verschillende studies zijn consequent en komen overeen met de resultaten verkregen met andere technieken. Men moet echter wel rekening houden met het feit dat de resultaten van één enkele opname niet steeds de residuele transportrichting weergeven van de langetermijndynamiek. Opeenvolgende metingen hebben immers aangetoond dat nagenoeg alle bodemstructuren hun asymmetrie kunnen veranderen en dus zowel een vloed- als een ebasymmetrie kunnen vertonen. Deze asymmetrieverandering wordt geïnduceerd door bepaalde hydro-meteorologische omstandigheden waarbij een dominante wind en deining uit een welbepaalde richting de vloed- of de ebstroom kunnen versterken. De snelheid van aanpassing is hierbij functie van de afmetingen van de bodemstructuren. Na het einde van de storm, zullen de bodemstructuren evolueren naar hun originele evenwichtsasymmetrie waarbij de snelheid van aanpassing opnieuw functie is van hun grootte. Dit betekent dat bodemstructuren gebruikt kunnen worden om residuele transportrichtingen af te leiden op een lange termijn, hoewel de effecten van externe factoren uitgefilterd moeten worden. De asymmetrie van heel grote bodemstructuren (hoogte > 8 m) kan als permanent beschouwd worden en kan hierdoor gebruikt worden om het residuele sedimenttransport op lange termijn (verschillende jaren) af te leiden.

- Kleinere structuren kunnen eveneens gebruikt worden als transportindicatoren maar hun gevoeligheid aan de heersende hydro-meteo condities dient eerst onderzocht.

Residuele transportrichtingen gebaseerd op tracerproeven

Een aantal tracerproeven werden uitgevoerd op het BCP en nabijgelegen stranden. Enkele van deze technieken werden toegepast om het residueel bodemtransport af te leiden.

- Radioactieve tracers werden gebruikt in de nabijheid van de haven van Zeebrugge en de meeste resultaten reflecteren de dominantie van de vloedstroom in de richting van Nederland en een kustwaarts transport wat het resultaat is van golfwerking gekoppeld aan stormweer. Een tracerproef op de Westdyck zandbank (Frankrijk) gaf een residueel bodemtransport naar het NO weer in de richting van de Vlaamse Banken.

- Fluorescerende tracerproeven werden uitgevoerd op de stranden ten oosten van Zeebrugge en bij Nieuwpoort, en gaven een oostwaarts residueel transport aan. Slechts één studie met fluorescerende tracers werd op zee uitgevoerd. Hierbij werd fluorescerend zand gestort op beide flanken van de Middelkerke Bank. Alhoewel de resultaten beïnvloed werden door een aantal factoren, kon een residueel transport in NO richting afgeleid worden op de westelijke bankflank en in ZW richting op de oostelijke flank. Sedimenttransport rond de bank kon eveneens afgeleid worden.

- Slechts één experiment met magnetisch zand werd uitgevoerd op het strand van Nieuwpoort. De resultaten hiervan gaven aan dat het tracersediment hoofdzakelijk in een ZW richting vervoerd werd.

Een aantal tracerproeven werd uitgevoerd om het suspensietransport af te leiden.

- Zes injecties van radioactieve tracers werden uitgevoerd. De resultaten wezen op een recirculatie naar de kustzone toe waar het sediment ingesloten wordt met een lichte dominantie van een sedimenttransport naar het NO. De resultaten moeten echter behandeld worden met de nodige omzichtigheid daar een aantal factoren de resultaten beïnvloed hebben.

- Een aantal natuurlijke tracers kunnen gebruikt worden om de residuele waterbewegingen op lange termijn en op grote schaal af te leiden. Saliniteitsmetingen, uitgevoerd op het Nederlands Plat, geven weer dat het water residueel vervoerd wordt in een NNO richting en dat de transportsnelheid stijgt van nagenoeg nul in de Belgische kustzone naar 6 cm/s nabij Texel. Residuele sedimentbewegingen kunnen eveneens afgeleid worden uit de verplaatsingen van minima van gesuspendeerde deeltjes en uit de oppervlakkige watertemperatuur gedetecteerd met thermische infrarood satellietbeelden.

De resultaten van de tracerproeven uitgevoerd op het BCP hebben nuttige informatie onthuld over de residuele transportrichtingen. De techniek kent echter niet altijd een succes daar bepaalde factoren een normale verspreiding van de tracerpartikels kunnen tegenwerken. Indien het gebied waar de tracerproef uitgevoerd wordt onderhevig is aan een sedimentaccumulatie, kunnen de tracerelementen bedekt worden door sediment waardoor ze niet meer beschikbaar zijn voor transport. Fluorescerende tracerexperimenten in zee steunen op uitgebreide staalnameoperaties wat de methode duur maakt. In dit geval is het wenselijk te steunen op andere tracertechnieken waarbij de detectie van de gemarkeerde partikels op de zeebodem plaatsvindt door een sleepsonde. Wegens de milieuonvriendelijke aard van radioactieve tracers, is het gebruik van magnetische tracers aan te raden.

Residuele transportrichtingen gebaseerd op sedimentdifferentiatie

Variaties in het ruimtelijk patroon van korrelgrootteparameters werden op verschillende manieren toegepast om residuele transportrichtingen af te leiden. Twee technieken, namelijk de Sediment Trend Analyse (STA) en een fractieanalyse, werden reeds toegepast op het BCP.

- Bij de STA, worden de korrelgrootteparameters gemiddelde korrelgrootte, sortering en scheefheid van een sedimentstaal vergeleken met de waarden van de buurstalen. Residueel transport treedt op indien een specifieke transporttrend voorkomt tussen 2 stalen. De meeste studies uitgevoerd op het BCP, geven weer dat de meest betrouwbare resulaten bekomen worden bij een combinatie van de transporttrends FB- (Fijner, Beter gesorteerd en negatievere scheefheid) en CB+ (Grover, Beter gesorteerd en positievere scheefheid). Trends waarbij de sortering verslechtert in de transportrichting, hebben weining gelijkenis met de transportrichtingen afgeleid met behulp van andere technieken.

- De STA werd toegepast op de volledige zuidelijke Noordzee, op de westelijke en oostelijke kustzone, op secties van de Kwinte Bank, Middelkerke Bank, Goote Bank en Ravelingen en op een gebied ten oosten van Zeebrugge. Een STA, toegepast op de volledige zuidelijke Noordzee, geeft weer dat een onderscheid gemaakt kan worden tussen twee verschillende gebieden: de kustzone in dewelke het transport gericht is naar het strand en een zeewaarts gebied waarbij transport naar het NO domineert. De resultaten van de STA uitgevoerd op de schaal van een kustsysteem en op secties van zandbanken zijn complementair met de transportrichtingen afgeleid met behulp van bodemstructuurasymmetrie. Het sedimentdynamisch model afgeleid uit de bodemstructuren waarbij zand residueel getransporteerd wordt op beide bankflanken door vloed- en ebstroom, wordt eveneens teruggevonden bij toepassing van de STA.

➢ De verschillende studies hebben aangetoond dat STA bruikbaar is om een inzicht te bekomen in de sedimenttransportrichtingen. Om residuele transportrichtingen af te leiden dienen de resultaten van de STA aangevuld met complementaire technieken en te beschikken over hydrodynamische gegevens. Het is eveneens aan te raden om een STA uit te voeren in één enkel sedimentair milieu.

➢ De studie van de distributie van de verschillende korrelgrootteklassen werd toegepast in de westelijke kustzone waar processen van vergroving, verfijning en uitwassen van specieke korrelgroottefracties geobserveerd en gerelateerd konden worden aan verschillende hydro-meteorologische omstandigheden. Relatief gezien, werden de grofste sedimenten geassocieerd met mooi weer condities en fijnere zandige sedimenten met ruwere omstandigheden aangezien deze onder deze condities in het systeem worden gebracht.

Residueel transport gebaseerd op metingen van stroming en concentraties van gesuspendeerde deeltjes

➢ Een groot aantal metingen van stroming en concentraties van gesuspendeerde deeltjes werden uitgevoerd op het BCP hoofdzakelijk in het kader van de uitbouw van de nieuwe buitenhaven van Zeebrugge. Deze korte-termijnobservaties verschaffen een inzicht in de grootte-orde van de suspensieconcentraties, weliswaar met een sterke fluctuatie in de tijd.

➢ Continue gegevens over stroomsnelheid en sedimentconcentraties gedurende een langere periode (springtij-doodtij) zijn bij voorkeur verkregen met behulp van instrumenten zoals Optical Backscatter Sensoren (OBS) of Acoustic Doppler Current Profilers (ADP). Deze metingen kunnen uitgevoerd worden vanuit het schip of vanaf de bodem door middel van instrumentenframes. Een klein aantal van deze metingen kon reeds op het BCP uitgevoerd worden. Metingen op de loswallen Zeebrugge Oost en S1 hebben het mogelijk gemaakt om het residueel suspensietransport nauwkeurig te bepalen gedurende springtij (tot 15 ton/m/dag), middeltij en doodtij (tot 4 ton/m/dag).

➢ Sedimentconcentratiemetingen in combinatie met multispectrale scannerregistraties vanuit een vliegtuig en een 2D hydrodynamisch model werden gebruikt om het suspensietransport te bepalen in de volledige kustzone. Het residueel transport was parallel aan de kust en vloeddominant voor nagenoeg de volledige kust. Residuele transportwaarden varieerden tussen 0.6 en 5 ton/m/dag.

Residuele transportrichtingen gebaseerd op sedimenttransportmodellen

De numerische transportmodellen, toegepast op het BCP, kunnen opgesplitst worden in suspensielading- en totale ladingmodellen.

➢ De cohesieve sedimenttransportmodellen van het BCP zijn regionale modellen met een groot aantal vereenvoudigingen (door de beperkte kennis van het fysisch milieu). De turbulentievelden, geparametriseerd als een fenomeen op kleinere schaal, de bodemsamenstelling en de grensvoorwaarden zijn slecht gekend door een gebrek aan veldgegevens. De bodemdynamiek (erosie en afzetting in functie van sedimentsamenstelling, transport, consolidatie) worden gesimuleerd gebruikmakende van vereenvoudigde relaties; het effect van biologische processen wordt niet in rekening gebracht.

- De processen verantwoordelijk voor de vorming van hoge turbiditeiten zijn de stromingen en de invoer van gesuspendeerde deeltjes doorheen het Nauw van Kales. Door het verminderen van het NO residueel transport en de ondiepte van het gebied, worden de gesuspendeerde deeltjes geconcentreerd in de Belgische-Nederlandse wateren en wordt een turbiditeitsmaximum gecreëerd nabij Zeebrugge. Het voorkomen van een turbiditeitsmaximum kan het best vergeleken worden met een sedimentstagnatie. De erosie van Tertiaire klei, Holoceen slib en veenlagen is gedeeltelijk verantwoordelijk voor de verhoging van de concentratie van de gesuspendeerde deeltjes in het beschouwde gebied.

- Fijne sedimenten worden continu afgezet en opnieuw in suspensie gebracht waarbij de concentraties verschillen in functie van de tijcyclus, van de doodtij-springtij cyclus en van hydro-meteorologische omstandigheden. Afzetting, resuspensie en transport van slib tijdens een tijcyclus zijn basisprocessen en zijn verantwoordelijk voor de concentratie van gesuspendeerde deeltjes in de zone van het turbiditeitsmaximum.

- De verschillen tussen dood- en springtij zijn gedeeltelijk verantwoordelijk voor het permanent karakter van de slibafzettingen. Gedurende doodtij, heeft het slib een hogere kans om te bezinken, te consolideren en zijn erosiegevoeligheid te verminderen. Meer slib wordt dan gevonden op de bodem en de concentratie van gesuspenderde deeltjes is relatief laag. Tijdens springtij wordt een deel van het bezonken sediment terug in suspensie gebracht.

- Een recent totale lading model gebruikt hydrodynamische en golfinformatie om het sedimenttransport te berekenen. De resultaten tonen een sedimenttransport op de zandbanken dat in wijzerzin verloopt: naar het NO op de westelijke bankflank en naar het ZW op de oostelijke bankflank. In het kustgebied (20 km) is het transport NO gericht, in het Scheur is deze gericht naar het W en in open zee (ten noorden van de zandbanken) verloopt het sedimenttransport naar het ZW.

Evaluatiecriteria

De ruimtelijke en tijdschaal waarop de residuele transportresultaten bekomen met verschillende methoden van toepassing zijn, kunnen sterk van elkaar verschillen. Alle technieken uitgevoerd op het BCP werden geklasseerd in een aantal ruimtelijke en tijdschalen. Vier categorieën werden gedefinieerd voor zowel tijdschaal (microschaal: uren tot dagen; mesoschaal: dagen tot weken; macroschaal: weken tot maanden; megaschaal: jaren tot decenia) als ruimtelijke schaal (microschaal: 0.1 tot 1 m); mesoschaal: 1 tot 100 m; macroschaal: 100 m tot 1 km; megaschaal: 1 – 100km).

Sedimentbudgettering

Met de bestaande gegevens is thans nog steeds moeilijk om een sedimentbalans op te maken voor het BCP. Kwantitatieve gegevens bestaan echter voor de menselijke activiteiten op het BCP zoals baggerwerken, zandextractie en strandopspuitingen.

- Jaarlijks wordt ± 1.4 x 10^6 Ton Droge Stof (zand) gebaggerd uit de navigatiegeulen
- Metingen geven weer dat 80-90% van het gestorte materiaal op de stortplaats blijft. De resultaten van de STA geven weer dat 10-20% terug vervoerd wordt naar de navigatiegeulen (dit komt overeen met 0.08 – 0.16 x 10^6 TDS van de loswal B&W S1 voor het baggerjaar 1997). De STA geeft eveneens aan dat het nieuwe sediment dat in de navigatiegeulen sedimenteert, uit het westen afkomstig is (Wenduine Bank, Wandelaar).
- Erosie komt voor langs sommige delen van de Belgische Kust. In de jaren '90 werd ongeveer 1.1 x 10^6 TDS/jaar zand aangevoerd voor strandopspuitingen.
- 2.5 x 10^6 TDS zand wordt per jaar gewonnen (90% is afkomstig van de Kwinte Bank).
- Volgens nationale en internationale studies wordt de globale sedimenttransit langs de Franse, Belgische en Nederlandse kust in NO richting geschat op 5 tot 10 x 10^6 TDS/jaar. Een schatting van 20 x 10^6 TDS/jaar werd in een recente studue naar voor gebracht voor het suspensietransport.

Op basis van een meetperiode van 40 dagen waarin stroom- en suspensieprofielen geregistreerd werden op de Middelkerke Bank, werden de volgende transporthoeveelheden bekomen:

- 0.9 Ton/m/dag (tot 30 cm boven de bodem) langs de steile flank; dit was 10 maal zo veel als langs de zuidelijke flank (0.05 Ton/m/dag); zandtransport verliep in de richting van de hoofdas van de stroomroos wat overeenkomt met een afwijking van 25° t.o.v. de bankas.
- Het sediment dat getransporteerd werd langs de steile flank had een korrelgrootte tussen 100 en 140 µm; deze fractie kwam niet in significante proporties voor in de sedimentstalen van de bankflank wat betekent dat dit sediment afkomstig was uit dieper water.
- Wanneer geen rekening gehouden wordt met de fijnere fractie, is de transporthoeveelheid van grover zand (>200 µm) gelijk op de 2 meetpunten over een periode van 40 dagen.
- De transporthoeveelheden zijn consistent met een tijdschaal van 100-1000 jaar voor de vorming van de bank.

Aanbevelingen

De nadruk wordt gelegd op een efficiënte kartering van de zeebodem met verschillende eindproducten die zowel belang hebben voor wetenschappers als eindgebruikers en dit zowel voor klein- als grootschalige toepassingen. Twee karteringstechnieken worden voorgesteld: multibeam en side-scan sonar. Beide technieken zijn complementair en in combinatie is een hoge resolutie morfologische-topografische kartering mogelijk inclusief een benadering van de zeebodemtextuur. Bovendien kunnen beide technieken op een kwantitatieve wijze de terugverstrooiingsgevevens (backscatter) verwerken waardoor met behulp van automatische classificatieprogramma's de sedimenttypes op een efficiënte en objectieve manier gekarteerd kunnen worden. Andere technieken bestaan echter eveneens en dienen verder onderzocht.

Terreinverificatie is een hoge prioriteit daar verder onderzoek naar de correlatie tussen akoestische parameters en sedimentkenmerken noodzakelijk blijft. Het nemen van niet-geroerde stalen in gebieden met een verschillend akoestisch facies maakt het mogelijk om zeebodemklassen te verifiëren en op die manier de voornaamste aggregaattypes voorkomend op het BCP akoestisch te definiëren. Hiervoor zal het echter steeds noodzakelijk zijn om te beschikken over geschikte staalnameapparatuur gecombineerd indien mogelijk met videobeeldopnamen. Deze benadering opent eveneens perspectieven voor biodiversiteitstudies.

Staalnameoperaties moeten zo efficiënt mogelijk gepland worden en moeten rekening houden met het grootschaliger sedimentair milieu. Het is dan ook aan te bevelen, vooral in het kader van monitoringstudies, om gebieden te bemonsteren die zo homogeen mogelijk zijn over een oppervlakte groot genoeg opdat een positioneringsfout op het staalnamepunt niet tot verkeerde besluiten zou kunnen leiden.

Hydrodynamische en sedimenttransportmetingen blijven van groot belang voor alle sedimenttransportstudies. Alhoewel een wiskundig model de meest geschikte techniek blijft om de lange termijn en grootschalige sedimentdynamiek te bestuderen, is het noodzakelijk om de modellen te voorzien van realistische gegevens van stroomsnelheid en sedimentconcentraties. Bovendien zijn de kwantificatie van het sedimenttransport en de hieruit volgende sedimentbudgettering belangrijk voor een duurzaam beheer van de zeebodem.

Voor sedimenttransportstudies blijven bodemframes, uitgerust met de nodige sensoren, en metingen verrichten over ten minste een doodtij-springtij cyclus aangewezen. Dit leidt tot gegevens van zowel het bodem- als suspensietransport waarbij de hoogte van de sensoren boven de zeebodem aangepast wordt in functie van de objectieven. Alhoewel deze configuratie toelaat om gedetailleerde informatie te bekomen over sedimenttransport, hebben de bekomen resultaten steeds betrekking op puntobservaties en extrapolatie naar een grotere schaal is dikwijls moeilijk.

Het gebruik van Acoustic Doppler Current Profilers gecombineerd met het gebruik van Optical Backscatter sensoren (met zorg gecalibreerd) laat toe, al varende, om de sedimentflux over de volledige waterkolom te berekenen. Het nadeel is echter dat de metingen veelal de zeebodem niet bereiken wat een ernstige tekortkoming is voor bodemtransportstudies. De ADP kan eveneens meten vanuit een bodemframe.

Een instrument dat over de mogelijkheid beschikt om de korrelgrootte van het sediment in suspensie in-situ te analyseren is de Laser In-Situ Scattering en Transmissometer (LISST). Dit type instrument is relatief nieuw en veelbelovend voor sedimenttransportstudies, maar het werd tot nu toe nog niet gebruikt voor onderzoeksdoeleinden op het BCP. Dit instrument kan eveneens gemonteerd worden op een frame en metingen verrichten over een periode van verschillende weken.

De sedimentdynamsche metingen op het terrein kunnen gebruikt worden als input, calibratie en validatie van numerische modellen. Huidige software laat toe hoge resolutie 2D of 3D hydrodynamische modellering van stroming en watertransport en dit zowel onder invloed van het getij als van verschillende hydro-meteo omstandigheden. Bovendien kunnen de voortplanting en transformatie van golven gesimuleerd worden met inbegrip van de golfevolutie onder verschillende windinvloeden, stroomsnelheden en waterdiepten. In combinatie met sedimenttransportmodellering (bodemlading, suspensielading en totale lading) kan de morfologische evolutie van de zeebodem gesimuleerd worden over een periode van dagen tot jaren.

Een voorbeeld van een toepassing van een geïntegreerde onderzoeksstrategie is een zeebodemmobiliteitstudie. De compilatie van nieuw verworven en bestaande data in combinatie met numerische modellering laat toe om de sedimenttransportcapaciteit van een gebied te evalueren en nieuwe inzichten te verwerven in de oorsprongsgebieden van de sedimenten.

Teneinde de efficiëntie en het praktisch gebruik van zeebodemgegevens te maximaliseren, is het noodzakelijk om alle beschikbare data te beheren met een Geografisch Informatie Systeem (GIS) waarbij het mogelijk wordt om data te selecteren in functie van de noden van de eindgebruiker. Dit zou bijvoorbeeld van groot nut zijn in het geval van de mariene aggegraatextractie. De nodige voorzorgen moeten wel genomen worden bij de geautomatiseerde productie van contourkaarten in het geval er geen kennis beschikbaar is over het desbetreffende sedimentair milieu.

Tenslotte is het aangewezen om richtlijnen en protocols op te stellen voor karteringsdoeleinden en staalnameoperaties wat het opstellen en evalueren van milieu-impactstudies sterk zou vereenvoudigen. Indien een GIS zou bestaan van de BCP mariene aggregaten zou gestandardiseerde achtergrondinformatie op een eenvoudige manier geproduceerd kunnen worden. In elk geval is een algemeen databeheer onontbeerlijk om toekomstige noden te voorzien en het nemen van beslissingen te vergemakkelijken.

ANNEX 1. Overview of sediment transport studies related to the BCS

ANNEX 2. Synthesis map of the natural sand transport on the BCS

ANNEX 3. Digital literature database regarding sediment transport studies related to the BCS

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OSTC

FEDERAL OFFICE FOR SCIENTIFIC, TECHNICAL AND CULTURAL AFFAIRS (OSTC)
SCIENTIFIC SUPPORT PLAN FOR A SUSTAINABLE DEVELOPMENT POLICY
Sustainable Management of the North Sea

INVESTIGATION OF THE NATURAL SAND TRANSPORT ON THE BELGIAN CONTINENTAL SHELF

BUDGET (Beneficial usage of data and geo-environmental techniques)

Annex 1

SEDIMENT TRANSPORT STUDIES RELATED TO THE BELGIAN CONTINENTAL SHELF

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Method used Asymmetry of bedforms
Details on used methodology The Southern Strait of Dover was mapped using different complementary techniques: side-scan sonar survey, bottom sediment sampling, bathymetry, current measurements and radioactive tracing.
Description of results Studies on the surficial morphology of sand bodies and other bedforms, and local investigations by radioactive sand tracing allowed the drawing of the general net sand transport pattern for the Southern Bight of the North Sea. According to the results, the English Channel North Sea borders are divided in two zones with respect to the net sand transport.
Deduced sediment transport directions The general pattern of sedimentary dynamics of the English Channel-North Sea border may be divided into (i) an axial and northern domain where the residual sand transport is southwestward (from the North Sea towards the English Channel) up to a NW-SE bed load convergence line and (ii) a southern coastal narrow and continuous domain where residual sand transport is northward and northeastward (from the English Channel towards the North Sea). The strong tidal currents of the region studied are considered as the main factor responsible for sand transport, while the swell plays an important but local role in maintaining particulate matter in suspension.
Publication BECK et al. (1991)
Time scale Compilation of all results: mega scale (years)
Space scale Compilation of all results: mega scale (several tens of km)

Method used Asymmetry of bedforms
Details on used methodology Sediment transport paths around the British Isles were deduced from bedforms such as sand ribbons, sandwaves and sand patches. Analysis is based on extensive recordings with the side-scan sonar Asdic.
Description of results In this study the asymmetry of sandwaves is used as an indicator of net sand transport direction. The longitudinal axis of sand ribbons is as well considered as a very reliable indicator of the flow line of the transport path (however additional data is needed to deduce the unique direction of net sand transport).
Deduced sediment transport directions The transport directions were derived on the continental shelf around the British Isles. The research was not extended on the Belgian shelf. A sand transport path in the Channel indicates net transport from the Atlantic towards the North Sea; in the Strait of Dover a bed-load parting zone occurs.
Publication KENYON and STRIDE (1968)
Time scale According to authors: mega scale (years)
Space scale According to authors: mega scale (tens to hundreds of km)

Method used Asymmetry of bedforms
Details on used methodology The analysis is based on the geometric characteristics of sandwaves. The bedforms were mapped along three tracks with the help of single-beam echosounding. These tracks were principally sailed in Dutch waters; however the southern extremities of the tracks are located north and west of the Hinder Banks.
Description of results The sandwaves west and north of the Hinder Banks have their steepest sides to the south. Further to the north the steepest side of the sand waves point to the north. Between these two mentioned areas many symmetric sandwaves are encountered. The height of the sandwave crests depends on the frequency of occurrence of heavy gales which erode the crests and the length of the intermediate calm weather period in which the crests are building up. The maximum observed variation in the height of the sand wave crests was about 2 m. Wandering megaripples (height 0.2-2 m) were observed on the flanks of the sandwaves. The crests of these current ripples often make an angle with the sandwave crests. In many locations it was observed that the traveling direction of these ripples, according to their asymmetry is directed towards the crest of the sandwave from both sides.
Deduced sediment transport directions The author does not support the use of the asymmetry of the sandwaves as an indicator for sand transport directions as there is no proof that the asymmetry of the sandwaves was created by the present-day hydraulic conditions.
Publication TERWINDT (1971)
Time scale None
Space scale None

Method used Asymmetry of bedforms
Details on used methodology The morphology of sandbanks and bedforms are used to propose a sequence of bank development. Bathymetric and side-scan sonar data are used in the analysis. The author relies however mainly on published information. Object of the study are the Norfolk Banks; however the Oost Dyck is as well considered.
Description of results Results on Oost Dyck: the steeper side of the bank, which lies at a maximum of 4° from the horizontal, faces northwest. Sandwaves averaging 0.3-06 m in height are present on both bank flanks. Both groups of waves face upslope. At the crest is a zone of symmetrical sandwaves where the opposing sand streams converge. Net movement in this zone would fluctuate greatly depending upon variations in current strength and meteorological conditions. According to the author, the asymmetry of the bank, with its steep side facing to the northwest, is a reflection of the dominance of the south-easterly moving sand stream.
Deduced sediment transport directions For the Oost Dyck: sandwaves are used to deduce net sediment transport directions: the movement of sand is directed towards the crestline from both sides of the bank.
Publication CASTON (1972)
Time scale According to authors: mega scale (years)
Space scale According to authors: mega scale (tens to hundreds of km)

Method used Asymmetry of bedforms
Details on used methodology The regional net sand transport directions are derived from the asymmetry of offshore tidal sandbanks.
Description of results
Deduced sediment transport directions Hinder Banks: a net sand transport direction in a NE direction Flemish Banks: a net sand transport direction in a SW direction Zeeland Ridges: primariliy a net sand transport direction in a NE direction Coastal Banks: a net sand transport direction in a coastwards to NE direction The sandbank groups are delineated through a sinuous bedload parting zone.
Publication KENYON et al. (1981)
Time scale Mega-scale
Space scale Mega-scale

Method used Asymmetry of bedforms
Details on used methodology Analysis based on a side-scan sonar mosaic (slant range of 100 m) and single-beam bathymetric recordings carried out on the Middelkerke Bank in May 1990. Both large and very large dunes (sandwaves) and small and medium dunes (megaripples) were studied.
Description of results The following results were obtained: • For large and very large dunes (defined hereafter as large dunes): almost every large dune on the bank can assume ebb and flood orientation through time. A correlation was found between the asymmetry of the bedforms and the prevailing meteo-marine conditions. The results suggest that dominant north-northeasterly swell and winds can induce an ebb-asymmetry in the large dunes. Similarly, a swell and winds from the southwest to west can cause the large dunes to be flood-asymmetrical. • For small to medium dunes (defined hereafter as small dunes): the lee slope of the small dunes dips in opposite directions on either side of the bank. In the western swale and western section of the bank they dip to the northeast whereas in the eastern swale and eastern section of the bank they dip towards the southwest.
Deduced sediment transport directions From large dunes: asymmetry is linked to the medium-term hydro-meteorological conditions. Persistent wind and swell from a particular direction influence the asymmetry of the bedforms. From small dunes: asymmetry of small dunes is opposite on both bank flanks suggesting a convergence of sand streams towards the crest line of the bank.
Publication LANCKNEUS and DE MOOR (1994) LANCKNEUS et al. (1994) LANCKNEUS et al. (1993b) (RESECUSED final report, Chapter 8)
Time scale Large dunes: macro-scale (weeks to months) Small dunes: meso-scale (days to weeks)
Space scale Large dunes: macro scale (hundreds of m up to 3 km) Small dunes: macro scale (tens to hundreds of m)

Method used Analysis of bedforms
Details on used methodology Analysis based on a side-scan sonar mosaic (slant range of 100 m and track spacing of 140 m) and single-beam bathymetric recordings carried out on the northern extremity of the Kwinte Bank during the winter period of 1989. Large and small dunes were considered to deduce residual sediment directions. The results of small dunes were compared with the results from Sediment Trend analysis.
Description of results The small dunes have their steep slope dipping dominantly towards the northeast; some bedform fields with their steep slope dipping towards the southwest occur on the eastern bank flank. All large dunes occurring on the bank have their steep slope dipping towards the northeast.
Deduced sediment transport directions From the large dunes a dominant sediment transport towards the northeast is derived on the sandbank itself. From the small dunes: transport towards the northeast in the western swale, on most of the bank and partly in the eastern swale; transport towards the southwest in the northern section of the eastern swale.
Publication LANCKNEUS et al. (1992) GAO et al. (1994)
Time scale Meso scale (days to weeks)
Space scale Macro scale (tens to hundreds of m)

Method used Analysis of bedforms
Details on used methodology Analysis based on a side-scan sonar mosaic (slant range of 75 m) and single-beam batymetric recordings carried out on the central part of the Goote Bank on 11 June 1992. Large and small dunes were considered to deduce residual sediment directions. The results of small dunes were compared with the results from Sediment Trend analysis.
Description of results Both small and large dunes cover both bank flanks and summit of the bank.
Deduced sediment transport directions A sediment transport towards the southwest can be deduced from both large and small dunes.
Publication VAN LANCKER (1993) LANCKNEUS et al. (1993a)
Time scale Large dunes: macro scale (weeks to months) Small dunes: meso scale (days to weeks)
Space scale Large dunes: macro scale (hundreds of m up to 3 km) Small dunes: macro scale (tens to hundreds of m)

Method used Analysis of bedforms
Details on used methodology The geometry of a number of large dunes on the northern part of the Kwinte Bank was studied. The analysis was based on side-scan sonar recordings (slant range of 100 m) and single beam bathymetric recordings carried out in February 1989, June 1989 and November 1989.
Description of results All three measurements showed that the large dunes had their steep slope facing the northeast. The recordings detected from February to June a shifting of the crests of the large dunes over a distance of 28 m towards the southwest. A second shift in opposite direction of the same magnitude took place between June and November returning the crests to the same position they had eleven months previously.
Deduced sediment transport directions Important here to notice is that the movement of the large dune occurred the first time in the direction of the gentle slope and the second time in the direction of the steep slope. This means that a dominant hydro-meteo condition can cause a sand transport to occur in the direction of the gentle slope and this without changing the original asymmetry of the large dune. In this case the original asymmetry still points to a longer-term process.
Publication LANCKNEUS and DE MOOR (1991)
Time scale Large dunes: macro scale (weeks to months)
Space scale Large dunes: macro scale (hundreds of m up to 3 km)

Method used Analysis of bedforms
Details on used methodology Bedforms in the area of the Flemish Banks (Kwinte Bank, Buiten Ratel and Oost Dyck and adjacent swales (Negenvaam, Kwinte and Buiten Ratel swale) were analysed by using side-scan sonar and bathymetric data recorded with a track spacing of 1400 m). All recordings took place in November 1986.
Description of results Both large and small dunes were mapped and their geometric characteristics were analysed.
Deduced sediment transport directions Based on the small dunes: the three sandbanks receive sand from both adjacent channels in opposite directions (residual flood currents dominate the western bank flanks while residual ebb currents dominate the eastern bank flanks). Along both flanks the residual sand transport becomes perpendicular to the bank axis, causing a sand up piling towards their central parts.
Publication DE MOOR and LANCKNEUS (1988a) DE MOOR and LANCKNEUS (1990)
Time scale Small dunes: meso scale (days to weeks)
Space scale Small dunes: macro scale (tens to hundreds of m)

Method used Analysis of sedimentary structures
Details on used methodology A total of 37 undisturbed samples were taken on the Buitel Ratel sandbank with a Reineck boxcorer of which lacquer peels were made. The bedform morphology was derived from a side-scan sonar recording. Interpretation of the sedimentary structures led to formulate a qualitative model for fair-weather sediment dynamics around the Flemish Banks.
Description of results Three main sedimentary facies (and 8 subfacies) were recognised: megaripple cross-bedding, horizontal bedding and disturbed bedding due to bioturbation. The steep NW flank of the Buiten Ratel is eroded during the flood stage and the amount of sediment received (partly from suspension) from the ebb is not high enough to compensate for the erosion. The mild SE flank is an aggradational area, in agreement with the regional dominance of the flood.
Deduced sediment transport directions Megaripples on both bank flanks have their steep slope dipping towards the bank axis which point to a sand up piling mechanism towards the bank crest.
Publication HOUTHUYS (1989) VLAEMINCK (1984) VLAEMINCK et al. (1989)
Time scale Meso scale (fine weather conditions period)
Space scale Macro scale (tens to hundreds of m)

Method used Analysis of bedforms
Details on used methodology In the period 1995-1999, an integrated sediment- and morphodynamical study was carried out in the western Belgian coastal zone including the Nieuwpoort Bank, Stroombank, Baland Bank, Westdiep, Grote Rede, Kleine Rede and the interaction zone with the Flemish Banks (southern part of the Middelkerke Bank and Ravelingen). Bedforms were determined from single-beam data and side-scan sonar recordings. Track spacing varied from 1 km to 75-50 m according to the specific aim and the complexity of the area. Sequential bathymetric surveys were carried out on the Baland Bank, Westdiep, southern part of the Middelkerke Bank and the Ravelingen. The results along the southern part of the Middelkerke Bank are reported in O'Sullivan (1997), those along the Ravelingen sandbank in Delgado Blanco (1998).
Description of results Both large and small dunes were mapped and their geometric characteristics were analysed.
Deduced sediment transport directions Generally, the larger bedforms in the near coastal area are flood-dominated (NE). Along the interaction zone with the Flemish Banks, the bedforms near the Grote Rede are flood-dominated whilst those near the eastern Flemish Banks' swales tend to be ebb-dominated and hence a convergence zone exists corresponding with the top zone of the sandbanks. An overall reversal of asymmetries was observed after a period of consisted NE winds.
Publication VAN LANCKER (1999)
Time scale Large dunes: macro scale (weeks to months) Small dunes: meso scale (days to weeks)
Space scale Large dunes: macro scale (> hundreds of m) Small dunes: macro scale (tens to hundreds of m)

Method used Analysis of bedforms
Details on used methodology Bedforms in the southern part of the Middelkerke Bank were studied on the basis of sequential single-beam bathymetric surveys and some side-scan sonar surveys (track spacing of 75 m). Data was analysed from September, November 1996 and May 1997.
Description of results Both large and small dunes were mapped and their geometric characteristics were analysed.
Deduced sediment transport directions Generally, the dunes near the Grote Rede swale are flood dominated, whilst those higher up the Middelkerke Bank tend to be ebb-asymmetric. All dunes can however change their asymmetry according to the ruling hydro-meteorological conditions.
Publication O'SULLIVAN (1997) VAN LANCKER et al. (1997)
Time scale Large dunes: macro scale (weeks to months) Small dunes: meso scale (days to weeks)
Space scale Large dunes: macro scale (> hundreds of m) Small dunes: macro scale (tens to hundreds of m)

Method used Analysis of bedforms
Details on used methodology Bedforms in the Ravelingen area were analysed on the basis of single-beam bathymetric data and some side-scan sonar registrations (track spacing of 75 to 150 m). Data was analysed from September and November 1997, February and March 1998.
Description of results Especially, the large, but also the small dunes were mapped and their geometric characteristics were analysed.
Deduced sediment transport directions The sandbank and the associated field of large dunes are generally flood-dominated (NE directed); whilst the dunes somewhat to the north, in the interaction zone with the Flemish Banks, are ebb-dominated (SW directed). These dunes are in the vicinity of an ebb-dominated swale. The differences in asymmetry between the north and south region are confirmed on a temporal basis.
Publication DELGADO BLANCO (1998) VAN LANCKER et al. (1998)
Time scale Macro scale (weeks –months)
Space scale Macro scale (hundreds up to 1 km)

Method used
Analysis of bedforms
Details on used methodology
• Bedforms in the shallow western coastal system Westdiep-Trapegeer-Potje-Broers Bank (0 to -15 m MLLWS) have intensively been studied. A preliminary bedform distribution was derived from existing single-beam data and compiled with sediment information (Honeybun 1999). Van Lancker et al. (2000b) combined the results with current measurements and performed sediment transport calculations. In the framework of the OSTC Habitat project (Degraer et al. 2001), the area was extensively surveyed using single- and multibeam data and full-coverage very-high resolution side-scan sonar data. The campaigns took place in September and October 1999, March and November 2000. The Westdiep area was additionally surveyed in October 1999, October and November 2001. • The side-scan sonar data was analysed and subdivided into different acoustic facies. 21 seabed classes were established mainly based on differences in reflectivity, texture, pattern and some primary descriptors. The classes were interpreted in terms of sediment packing, bedforms, sedimentology, processes and depositional environment (Van Lancker et al. in prep.).
Description of results
• A highly diverse and complex distribution of small to medium dunes was observed constituting of fine, medium and coarse sands as well as of shell hash. Fine to medium sandy small to medium dunes occur on the flanks of the sandbanks. Sandy to shelly medium to large dunes occur along the zone of positive relief in the Westdiep swale. On the top of the shallowest areas, coarse-grained symmetrical wave ripples occur. • Large dunes occur where medium to coarse sands predominate. At the end of a zone of positive relief in the Westdiep swale, 1 dune of nearly 3 m occurs partly constituting of shell hash and partly of medium to coarse sand. Along the west of the Trapegeer sandbank, in water depths shallower than - 6 m MLLWS, 4 compound dunes exist. Their strike and asymmetry seems to be conditioned by the ebb tidal current. Their height varies around 2 m. Some large dunes occur in the erosional trough associated with the Broers Bank and are clearly ebb-shaped. In the shallowest area, near the coast (0 m MLLWS), some compound dunes exist, mainly consisting of shell hash.
Deduced sediment transport directions
• In the Westdiep swale the strike of the medium to very large dunes is perpendicular to the maximum current velocities. The large dune, near the axis of the Westdiep swale, is clearly dominated by the flood current and is indicative of the regional sediment transport direction. However, the zone of positive relief towards the Trapegeer sandbank is characterised by medium to large dunes that tend to be ebb-asymmetric. • The dunes along the Trapegeer have an ebb-shaped strike and the large dunes are ebb-dominated. The same holds true for the large dunes south of the Broers Bank and along the shoal towards the coast. This is likely due to the higher resuspension potential of the ebb tidal current, which is of high importance in the shallowest areas.
Publication
HONEYBUN (1999); VAN LANCKER et al. (2000); RENNIE (2000); DEGRAER et al. (2001); VANSTAEN (in prep.); VAN LANCKER ET AL. (in prep.)
Time scale
Macro scale (weeks –months)
Space scale
Macro scale (100 m- 1 km)

Method used
Analysis of bedforms

Details on used methodology
Charlet (2001) studied the bedforms in the area east of Zeebrugge, north of the Paardenmarkt shoal. Single- and multibeam data was used from Waterways Coast Division. In September 2000, additional multibeam recordings were performed with a track interval varying between 500 m NW of the Paardenmarkt shoal up to 1 km to the north. In October 2000, limited very-high resolution side-scan sonar imagery was obtained perpendicular to the coastline (5 km). The study also integrated results of MUMM's BCZ model (750 m grid resolution).

Additionally, bottom-mounted acoustic doppler current profiling measurements were analysed carried out NW of the Paardenmarkt shoal.

ID	Location	Easting (m)	Northing (m)	Start	End	Type ADCP
PM	Paardenmarkt	515982	5691571	2000-09-05 09:22	2000-09-06 10:55	RDI Workhorse sentinel 1200 kHz ADCP

Description of results
Generally, bedforms are rare which is mainly due to the predominance of very fine to fine sands, largely enriched with mud. Small to medium dunes do occur north of the sandy shoal and along the eastern extremity of the Paardenmarkt munition dumpsite with a strike more or less perpendicular to the coastline. Interestingly, a field of large to very large dunes (with dune heights of up to 2 m) occurs north of the Paardenmarkt shoal, in the Wielingen area.

Deduced sediment transport directions
On the basis of the characteristics of the small to medium dunes, transport directions can be deduced more or less parallel to the coastline, but as well flood- as ebb-dominated. Given the shallowness of the area (- 2 to - 10 m MLLWS), it seems likely that these bedforms are too sensitive to be used for residual transport directions.

The large to very large dunes have also a strike more or less perpendicular to the coastline. Interestingly, the western dunes have a flood-dominated asymmetry, whilst some dunes at the eastern part are ebb-dominated. A zone of symmetrical dunes exists between both. Together with the sediment trend analysis results and the numerical modelling, it can be deduced that the field of larger dunes represents a zone of bedload convergence, which can slightly shift in space according to the ruling hydro-meteo conditions.

Publication
CHARLET (2001)

Time scale
Macro scale (weeks –months)

Space scale
Macro scale (100 m- 1 km)

Method used Analysis of bedforms
Details on used methodology A single- and multibeam reconnaissance survey was carried out in the Hinder Banks region in October and November 2000. A track spacing of 2 km was chosen covering the different sandbank and swale systems. 70 samples were taken to characterise the surficial sediments and to calibrate an automated acoustical seafloor characterisation on the basis of the multibeam data. The seabed mobility of the area was evaluated using numerical modelling results of MUMM's mu-BCZ model (750 m grid) including residual currents and water transport. The results were dynamically integrated with existing literature data and reports (including subsurface data).
Description of results 964 large dunes were determined and mapped including their height and strike Large dunes were well spread over the area as well on the sandbanks as in the swales. The highest dunes (up to 11 m) occur in the north.
Deduced sediment transport directions From the asymmetry of the large dunes, residual bedload transport seems to be controlled by the ebb current (SW) (42 % of the large dunes were ebb-asymmetric; 32 % was symmetrical and 26 % was flood-asymmetric). This is in line with residual water transport directions based on the mu-BCZ model. Generally, the western bank flanks are flood-dominated and the eastern flanks are ebb-dominated. Veering of the dune crest lines towards the sandbank tops was observed, whilst deeper, the strike of the dunes was perpendicular to the axis of the swale. Based on several arguments, it should be evaluated whether the Hinder Banks region is a source area for the Flemish Banks.
Publication DELEU (2001)
Time scale Macro scale (weeks –months)
Space scale Macro scale (hundreds up to 1 km)

Method used Analysis of bedforms
Details on used methodology Multibeam data and side-scan sonar recordings were carried out along the entire Belgian coastline (October and November 2000, May and October 2001). Seven transects were sailed perpendicular to the coastline, whilst in the Wenduine Bank region, data was recorded along parallel and perpendicular track lines. Samples were taken to characterise the surficial sediments and to calibrate an automated acoustical seafloor classification based on the multibeam and side-scan sonar data. The interpretation will be aided by numerical modelling results including residual currents and water transport.
Description of results Both large and small dunes will be mapped and their geometric characteristics analysed.
Deduced sediment transport directions
Publication DEGRAER, VAN LANCKER & MOERKERKE ET AL. (in prep.) VANSTAEN (in prep.)
Time scale Macro scale (weeks –months)
Space scale Macro scale (100 m- 1 km)

Method used Asymmetry of bedforms (sandwaves), direction of strongest tidal current at the sea surface
Details on used methodology Conventional single-beam echosounding and echo-ranging equipment (primitive side-scan sonar) were carried out around Southern Britain between 1952 and 1961. The asymmetry of sandwaves was deduced from these recordings.
Description of results The steep slope of the sandwaves was used to indicate the direction of sand transport.
Deduced sediment transport directions Transport paths on the Belgian shelf present two main directions: a northeastern direction in a coastal area and a southwestern direction more offshore. These directions coincide with the directions of the strongest tidal currents at the sea surface. The sediment in the coastal area moves along a front about 40 miles wide and is moving northwards out of the Southern Bight of the North Sea. A radio-active tracer study of the Scheldt Estuary confirms this northward transport. Estimates of sand being moved: • 600 m^3 is moved through the Strait of Dover into the North Sea (low figure explained by the relative shortage of sand in the Strait). • 4×10^6 m^3 would be crossing a plane 40 miles wide each year.
Publication STRIDE (1963)
Time scale According to authors: mega scale (years)
Space scale According to the author: mega scale (tens to hundreds of km)

Method used Asymmetry of bedforms
Details on used methodology Research was based on single-beam echosounding, ASDIC equipment (± side-scan sonar), sand corer, water-jet sampling apparatus and a sparker.
Description of results Results focus on the morphology, sedimentology, internal structures of the sandbanks of the Well Bank area, the Hinder group, the Flemish Banks and another number of individual banks.
Deduced sediment transport directions • For the Hinder Banks: both on the sandbanks and in the swales asymmetric sandwaves were found. From the fact that south-pointing asymmetric sandwaves predominate over north-pointing ones, it was deduced that sand transport over the sandbanks was towards the southwest. • For the Flemish Banks: the author mentions a great abundance of sandwaves on the Flemish Banks but admits that he does not understand their orientation. Hence no sand transport directions were deduced.
Publication HOUBOLT (1968)
Time scale According to author: mega scale (years)
Space scale According to author: mega scale (tens of km)

Method used Fluorescent tracers Fall-out products of nuclear tests
Information on used method
Description of results The fall-out products of nuclear tests in 1963 resulted in a generally distributed artificial tracer. The localisation of higher concentrations was indicative of actual deposition and witnessed the muddy sedimentation along the Belgian coast.
Deduced sediment transport directions Residual transport of beach sand occurred mainly northeastwards.
Publication BASTIN (1974)
Time scale Mega scale (years-decades)
Space scale Mega scale (several tens of kilometres)

Method used
Fluorescent tracers

Information on used method
Nine fluorescent tracer experiments were carried out on three beaches eastwards of Zeebrugge (Heist, Duinbergen (Albert beach) and Knokke (Lekkerbek beach)). A total of 35 kg fluorescent sand with a mean of 220 µm was used for each experiment. Two injections were carried out simultaneously on each location: one with red sand on the foreshore and one with green sand on the backshore. The measurements took place from September 77 to January 78. Iso-concentration lines around the injection point were drawn to deduce the residual transport directions.

Description of results
Results can be summarised as follows:

beach	*period*	*transport (in m³/m/day)*	*direction*
Albert strand a	13 Sept.-3 Oct. 77	3.6	eastwards
Albert strand b	15 Nov.-1 Dec. 77		
Lekkerbek strand	13 Oct.-2 Nov. 77	3.2 to 24.5	eastwards
Heist strand	10 Jan.-19 Jan. 78	9.1 to 10.8	eastwards

Deduced sediment transport directions
Residual transport of beach sand occurred mainly eastwards; a transport seawards took place along the breakwaters; transport rate increased with wave height.

Publication
TIJDELIJKE VERENIGING ZEEBOUW ZEEZAND and HAECON-ZEEBRUGGE STUDIEGROEP T.V.Z.2. (1978b)
BASTIN et al. (1983)

Time scale
Meso scale (1 to 2 months)

Space scale
Meso scale (up to 100m)

Method used Fluorescent tracers
Information on used method A fluorescent tracer experiment was carried out on the beach between Bredene and De Haan (near Kilometre Pole 42). A total of 100 kg fluorescent sand was placed on a sand ridge at low tide. The marked sand was put in a pit of 5 cm depth (surface of area: 1.5 x 1.5 m) after which it was covered with a thin layer of natural sediment. Samples were taken three times (up to 10 days after start of experiment) during low tide by using a radial grid centred in the immersion point. Samples were taken with plastic tubes after which they were dried and split in a representative sample. The fluorescent grains were counted using a fluorescent light.
Description of results The residual transport took mainly place in an onshore direction. During the period of the experiment, profiling measurements showed clearly that the area was subject to an accumulation of sand.
Deduced sediment transport directions During the experiment transport occurred mainly in a landward direction. A small eastward component could however as well be deduced.
Publication IGNACIO RUIZ GARCIA (1994)
Time scale Meso scale (10 days)
Space scale Meso scale (samples were taken up to 20 m from injection point)

Method used Fluorescent tracers
Information on used method A fluorescent tracer experiment was carried out on a ridge and runnel beach, west of the pier of Nieuwpoort. A total of 15 kg moisturized fluorescent sand (fraction 50 µm to 1 mm) was placed on a sand ridge at low tide in a pit of 30 to 40 cm and 15 cm deep. Additionally, 15 kg moisturized fluorescent sand was spread over the beach to also assure a movement of the tracer under calm weather conditions. In the period 10-14/04/1995, daily samples (40) were taken at low water by using a radial grid centred in the immersion point accompanied by topographic measurements (total station). The samples were retrieved with a bulb device allowing obtaining a standard volume of about 2300 cm^3. The fluorescent grains were counted by means of electronic photography.
Description of results Due to calm weather conditions, no significant sediment transport was observed on 10-11/04; tidal action took care of the natural build-up of the ridges. From April 12-14, N-NE winds blew with a speed of 8-9 m/s. The concentration maxima shifted to the S to SW due to wave-induced currents. Some contour lines of the sand ridge digital terrain model were 50 m displaced. It was stated that the movement of the tracer grains was representative for the sediment transport on the ridge.
Deduced sediment transport directions A net sediment transport was derived in a SW direction, which was attributed to the N-NE winds in that period.
Publication BROEKAERT (1995) MOERKERKE (1995)
Time scale Macro scale (several days)
Space scale Macro scale (tens of metres)

Method used Fluorescent tracers
Information on used method During the MAST2-CSTAB project two releases of fluorescent sand (one red, one blue) of 500 kg each were carried out on the both flanks of the Middelkerke Bank on the 15th December 1992. The mass of sand slided into the sea at slack water using a specially prepared board. A total of 229 grab samples were collected afterwards during four separate surveys carried out on the 17th December 1992, 27 February 1993, 10 August 1993 and 20 July 1994 respectively. During the first two campaigns the samples were not taken in a grid but rather along one long line. This was probably the reason why the tracer sand was missed in many sampling points. All samples were inspected under ultraviolet light for the presence of fluorescent tracer while still wet. Selected samples were then dried and split into a 50 g sub-sample using a riffle box. This sub-sample was subsequently spread out over a black gridded card, inspected under UV light, and the number of grains of fluorescent tracer counted.
Description of results It should be noted that more than 88 % of the blue tracer grains and 95 % of the red tracer grains were 'apparently' lost in the first 2 days following deployment. It remains open to question whether the bulk of tracer grains were buried either at the source or at other locations during transport. Therefore, the results are restricted to a qualitative description. In general it would appear that sand is being moved both along and across the bank in both directions.
Deduced sediment transport directions Preferred movement along the bank during the first two campaigns, from what can be deduced from the results of the tracer used on the northwestern bank flank, is in a northeast direction. The later surveys (3 and 4) support the suggestion that the tracer grains dumped at the northwestern flank have moved around the Middelkerke Bank in a clockwise direction. These results were supported strongly by computed residual current vectors and are consistent with existing theory The only conclusion that can be drawn for the tracer used on the southeastern bank slope, is that there appears to be definite movement across the bank seawards.
Publication BARRACLOUGH (1993), O'CONNOR (1996), WILLIAMS (2000)
Time scale Mega scale (2 days up to 1.5 years) (no other reference was found on the fact that fluorescent grains could still be found after such a long period; the risk of contamination, mentioned by the authors of the study, can not be ruled out)
Space scale Mega scale (if the tracer really was transported around the bank: several km)

Method used Fluorescent
Information on used method During the MAST2-CSTAB fluorescent tracer experiments were carried out on the Nieuwpoort beach. The tracer was put into a 1 m x 1 m x 0.05 m pit during low water in the intertidal zone at Nieuwpoort beach. The pit was then covered with 5 mm natural sand. During the first fluorescent experiment (F1, 28/02/1994) the tracer (50 kg of green sand) injection was at the outer region of the high-tidal zone, the tracer was followed only a single tide, due to masking of the fluorescence by shell fragments, which made results unreliable for further quantitative analysis. During the second fluorescent experiment (F2, 26/02-01/03/1994) the tracer (40 kg of red sand) was released on the upper mid-tidal zone, near the lower limit of the high tidal zone. Measurements took place over 3 consecutive tidal cycles. During the third fluorescent experiment (F3, 02/03-04/03/1994) the tracer (50 kg of blue sand) was released on the central ridge in the mid-tidal zone, the tracer was followed during 5 tidal cycles.
Description of results
Deduced sediment transport directions There is a tendency for the tracer to be dispersed in response to wave direction and towards the northeast, i.e. in direction of the mean longshore current. There is also an onshore movement of the ridge system at an average rate of ±1 m per tidal cycle.
Publication O'CONNOR (1996), HUNTLEY and MACDONALD (1996), VOULGARIS et al. (1998)
Time scale Meso scale (several tidal cycles)
Space scale Macro scale (275 m x 200 m on intertidal zone of Nieuwpoort beach)

Method used Magnetic tracers
Information on used method The method used on the beach of Nieuwpoort belongs to the "active" tracing methods. In this case the magnetic susceptibility of the sands are artificially enhanced. The magnetic enhancement process involves heating the sand at high temperatures (700 °C) for two hours in a reducing atmosphere followed by rapid cooling in air. The material used in this experiment was sieved and magnetic susceptibility values for each particle size were obtained. These values were multiplied by the percentage weight of ech phi size to establish particle size contributions to the bulk sample. Approximately 100 kg of tracer material was placed in a pit 0.5 x 1.5 x 0.06 m (May 1993). The sand was wetted with a solution of local seawater and detergent. The tracer was then compacted to replicate as well as possible the surrounding conditions. A 12 x 12 m grid was constructed around the pit. At each low tide the grid was reconstructed using a theodolite. Magnetic susceptibility measurements were carried out in the centre of each grid cell using a Bartington Susceptibility meter and surface loop sensor. The first tracer site (M1) was on the seaward side of the highest ridge on the foreshore (near F2 and F3). The second site (M2) was in a runnel, which was permanently filled with water. The third tracer site (M3) was located on the landward side of the second ridge in the foreshore. The fourth site (M4) was a temporarily filled channel near the high water mark.
Description of results Measurements took place during 23 days and the magnetic susceptibility values were used to construct contour maps.
Deduced sediment transport directions Only a minor movement in northeasterly direction occurred. The majority of the mobilised tracer material was transported and deposited in a southwestern direction. A shift in direction from a southerly to a southwesterly direction can be explained by the change in wave direction with wave angle becoming more oblique by the third low tide.
Publication VAN DER POST et al. (1994)
Time scale Meso scale (23 days)
Space scale Meso scale (20m)

Method used
Radio-active tracers (bottom transport)

Information on used method
Seven tracer experiments were carried out eastwards of Zeebrugge. The used isotope was Ir 192 and the tracer grains had a mean value of 225 μm. The tracer material was released in the direct vicinity of the bottom with the help of an immersion device, which was lowered on the seabed. Detection was carried out with a sledge equipped with scintillation counter, which is pulled over the seabed along a number of lines parallel and perpendicular to the main sediment transport axis. Measurements took place from October 77 till May 78.

Description of results
Results can be summarised as follows:

site	*co-ordinates Lambert 72*	*period measurement*	*direction transport*	transport (m^3/m/day)
Western Appelzak	74.317;228.358	Okt.77-Dec.77	N75°E	2.5
Eastern Appelzak	77.106;229.251	Okt.77-Jan.78	N185°E	0.5
North of Appelzak	76.858;229.780	Okt.77-Jan.78	N75°E	0.1
West of Paardenmarkt	71.178;227.480	Dec.77-March 78	N160°E	0.05
Belgian-Dutch border	79.177;230.502	Dec.77-March 78		negligible
Wielingen	69.718;230.842	Feb.78-May 78	N232°E	1.8
W of Pas van het Zand	64.532;227.864	Feb.78-May 78	N275°E	0.04

Deduced sediment transport directions
Results concerning the directions of residual bottom transport over a period of several months were obtained. Quantitative results are only approximate.

Publication
TIJDELIJKE VERENIGING ZEEBOUW ZEEZAND and HAECON-ZEEBRUGGE STUDIEGROEP T.V.Z.2. (1978b)
BASTIN et al. (1983)
CAILLOT et al. (1978)

Time scale
Macro scale (3 months)

Space scale
Macro scale (1500 m)

Method used

Radio-active tracers (bottom transport)

Information on used method

Five tracer experiments were carried out around Zeebrugge to assess the bottom transport. The used isotope was Ir 192 and the tracer grains had a mean value of 220 μm. The tracer material (500 g) was released in the direct vicinity of the bottom with the help of an immersion device that was lowered on the seabed. Detection was carried out with a sledge equipped with scintillation counter, which is pulled over the seabed along a number of lines parallel and perpendicular to the main sediment transport axis. Measurements took place from September 1978 till January 1979.

Three additional injections (1 to 2 m under the water surface) of tracers (using the isotope Au 198) were carried out to measure the suspension transport. The detection of the radio-active cloud was achieved by towing immersed detectors at different depths.

Description of results

Bottom transport results:

site	co-ordinates Lambert 72	period measurement	direction transport	transport (kg/m/tide)
North Wandelaar	56.958;233.655	Oct.78-Jan.79	N41-221°E	negligible
Access channel Zeebrugge	54.945;235.311	Oct.78-Jan.79	-	negligible
Akkaert Bank	48.479;234.886	Oct.78-Jan.79	N50-230°E	negligible
Sierra Ventana (STI1)	59.996;238.640	Oct.78-Jan.79	N45°E	2
Dumping site STI2	56.931;240.609	Oct.78-Jan.79	-	1

Suspension transport results (no information found concerning sediment transport):

site	co-ordinates Lambert 72	period measurement	direction transport	transport (m^3/m/day)
Pas van het Zand (W)	64.240;229.837	Nov.78-Jan.79		
Pas van het Zand (E)	68.963;230.652	Oct.78-Jan.79		
Access channel Zeebrugge	57.722;235.330	Jan.79		

Deduced sediment transport directions

Results concerning the directions of residual bottom transport over a period of several months were obtained. Quantitative results are only approximate.

Publication

TIJDELIJKE VERENIGING ZEEBOUW ZEEZAND and HAECON-ZEEBRUGGE STUDIEGROEP T.V.Z.2. (1979)

BASTIN et al. (1983)

Time scale

Macro scale (4 months)

Space scale

For the bedload tracer: macro scale (1500 m)

Asymmetry of bedforms | **Tracers** | Suspension measurements | STA | Models | Others

Method used Radio-active tracers (bottom transport)
Details on used methodology Eight tracer experiments were carried out in the Channel. The used isotope was Ir 192 and the tracer grains had a mean value between 160 and 315 μm. Detection surveys were conducted during six months starting from 10/09/86.
Description of results The transport rates varied between 0.03 m^3/linear metre/day (for the area of the West Dyck, western part of the Flemish Banks) to 0.25 m^3/linear metre/day (for the area of the Bassure de Baas in front of Boulogne Sur Mer).
Deduced sediment transport directions According to calculations and radio-active tracing, quantitative estimations give a regional value of drag sand transport of 0.2 m^3/linear metre/day more or less parallel to the coastline a northeast direction.
Publication BECK et al. (1991)
Time scale Macro scale (months)
Space scale Macro scale (500 to 1000 m)

Method used Radioactive tracers (suspension transport)
Details on used methodology Three tracer experiments with long-life radioisotopes to study the dispersion of dumped matter (mud) have been carried out. After the dumping of the radioactive tracer (±4 kg of mud injected with Hf or Tb) some coastal, harbour and offshore stations were regularly measured by taking bottom samples. The aim of the measurements was to qualitatively gain inside into the transport and dispersion of suspended sediments. The first experiments (sx1) started on 22/04/1992 with dumping of matter on the dumping places B/2 (B&W S2, UTM: 5698142 N, 509848 E) and B/6 (B&W Zeebrugge Oost, UTM: 5691679 N, 518561 E). Seven measuring campaigns were carried out during the 174 days after dumping (end=13/10/1992). The second experiments (sx2) started on 18/01/1993 with dumping at the 'Noordflank Akkaert' (UTM: 5703840 N, 500672 E) and at the 'Ebschaar B/1 and B/2' (UTM 5701580 N, 507011 E, 17h08-17h28). Fourteen measuring campaigns were carried out during the 162 days after dumping (end=23/06/1993). The third experiments (sx3) started on 29/09/1993 with dumping at 'Negenvaam' (UTM: 5688800 N, 482000 E) and at the 'Noordflank Thornton' (UTM: 5713000 N, 499000 E). Eighteen measuring campaigns were carried out during the 190 days after dumping (end=07/04/1994)
Description of results The main conclusion, which can be derived from the data, is that (part) of the tracer dumped within ±20 km off the coast is recirculating rapidly towards the coast and is migrating into the Westerschelde. No conclusion can however be made on the quantities involved, since most of the bottom samples were taken near the coast. The radioactive mud dumped at site sx3-Thornton (open sea) was not detected along the coast. Results were partly biased by position and number of samples taken afterwards. A limited exchange with the offshore is deduced but nearly all sample sites were located in the near-coastal area.
Deduced sediment transport directions The residual suspended sediment transport direction offshore (>20 km) is parallel to the coast and towards the NE. The dumping of tracer in the coastal area do not allow to indicate a residual direction.
Publication HAECON (1992a); HAECON (1992b); HAECON (1994)
Time scale Macro scale (6 months)
Space scale Mega scale (BCS)

Method used Large scale tracer (salinity)
Details on used methodology Residual currents in the Southern Bight of the North Sea were analysed by applying salinity as tracer (in fact patches of fresh water from the discharge of Rhine-Meuse). Salinity was measured (from 1976 to 1983) on intervals of 14 days at locations in the Dutch coastal area ranging from 1 to 70 km offshore; a additional salinity time-series recorded at light vessel Noord-Hinder from 1953 to 1981 was as well analysed. This method is suitable to reveal large time- and length scales.
Description of results North of the Schelde estuary a residual current of 0.5 cm/s is calculated parallel to the coast going NE-ward. Time-variability of the residual velocity is mainly introduced by varying wind stress.
Deduced sediment transport directions In the Dutch coastal zone (between 0 and 30 km offshore) the residual velocity increases going NNE-ward, from almost zero near the Belgian coast to about 6 cm/s near the isle of Texel. The residual velocity amounts to 3.0 cm/s, NNE-ward, 70 km from the Dutch coast.
Publication VISSER (1989)
Time scale Mega scale (several years)
Space scale Mega scale (tens to hundreds of km)

Method used Thermal infrared imagery
Details on used methodology The superficial water temperature can be used as a tracer and can reveal long-term advective movements.
Description of results The principal flux of the Atlantic waters is directed straight towards the Strait of Dover.
Deduced sediment transport directions Nihil
Publication JEGOU and SALOMON (1991)
Time scale Macro scale (a few weeks)
Space scale Mega scale (tens to hundreds of km)

Method used

Water samples (suspension measurements)

Information on used method

Measurements of current (Ott meters), water depth and sediment concentration (by taking water samples in Nansen bottles) were carried out along four tracks, transversal to the coast (track 1: near Cadzand; track 2: on the Belgian-Dutch border; track 3: across the central part of the Appelzak; track 4: across the dumping site Paardenmarkt) during one tidal cycle.

Description of results

Results are given in the following table.

Track	*sample*	*co-ordinates Lambert 72*	*period measurement*	*direction transport*	*transport (kg/m/tide)*
1	1	83.578;231.694	1 tide (August 77)	N250°E	2000
1	2	83.335;232.316	1 tide (August 77)	N260°E	41500
1	3	83.092;232.999	1 tide (August 77)	-	
2	4	79.949;224.950	1 tide (August 77)	N67°E	3000
2	5	79.658;230.664	1 tide (August 77)	N250°E	15500
2	6	79.340;231.472	1 tide (August 77)	-	
2	7	79.023;232.311	1 tide (August 77)	-	
3	8	76.167;228.642	1 tide (August 77)	N208°E	3500
3	9	75.887;229.357	1 tide (August 77)	N77°E	11500
3	10	75.495;230.383	1 tide (August 77)	N276°E	9500
3	11	75.048;231.564	1 tide (August 77)	-	
4	12	73.552;227.641	1 tide (August 77)	N132°E	5000
4	13	73.284;228.347	1 tide (August 77)	N78°E	2000
4	14	72.819;229.555	1 tide (August 77)	N253°E	13000
4	15	72.329;230.835	1 tide (August 77)	-	

Transport in suspension is forty times more important than bottom transport.

Deduced sediment transport directions

The residual transport directions of the sediment in suspension were obtained and the sediment rate over one cycle was quantified.

Publication

TIJDELIJKE VERENIGING ZEEBOUW ZEEZAND and HAECON-ZEEBRUGGE STUDIEGROEP T.V.Z.2. (1978a)
HAECON (1982)

Time scale

Micro scale (one tide)

Space scale

Meso scale (point measurement)

Method used

Water samples (suspension measurements)

Information on used method

Measurements of current (Ott meters), water depth and sediment concentration (by taking water samples in Nansen bottles) were carried out in a number of points located in or near the 'Pas van het Zand' during one tidal cycle.

Description of results

Results are given in the following table.

site	*co-ordinates Lambert 72*	*tide phase*	*day measurement*	*direction transport*	transport (kg/m/tide)
ST1a	67.900;228.300	neap	18/07/75	N263°E	750
ST1b	67.900;228.300	middle	29/07/75	N234°E	4.000
ST2a	67.600;229.500	neap	17/07/75	N246°E	5.900
ST2b	67.600;229.500	middle	28/07/75	N241°E	9.200
ST3a	67.700;228.300	middle	04/07/76	N99°E	3.800
ST3b	67.700;228.300	spring	28/07/76	N246°E	6.200
ST4a	68.450;228.600	middle	05/08/76	N300°E	3.200
ST4b	68.450;228.600	spring	29/07/76	N254°E	1.600
ST5	66.100;229.950	-	-	-	-
ST6	67.000;230.150	-	-	-	-
ST7	68.300;227.500	middle	02/07/76	N224°E	3.050
ST8	69.350;227.800	middle	03/07/76	N115°E	13.500
ST9a	66.700;229.000	spring	27/07/76	N253°E	5.200
ST9b	66.900;228.900	middle	16/07/76	N260°E	4.500
ST10	67.900;229.250	middle	26/07/76	N260°E	2.700
ST11	64.800;231.400	spring	11/08/76	N84°E	1.000
ST12	65.500;231.650	spring	12/08/76	N87°E	300

Sediment concentration profiles made for different depths: 0.5 m, 1.0 m, 2.0 m and 3.0 m above the seabed, half of water column and 1.0m under water surface.

Deduced sediment transport directions

The residual transport directions of the sediment in suspension were obtained and the sediment rate over one cycle was quantified.

Publication

GULLENTOPS et al. (1977)

TIJDELIJKE VERENIGING ZEEBOUW ZEEZAND and HAECON-ZEEBRUGGE STUDIEGROEP T.V.Z.2. (1978a)

HAECON (1982)

Time scale

Micro scale (one tide)

Space scale

Meso scale (point measurement)

Method used Current measurements
Details on used methodology Current measurements were made from the North Hinder lightship (51°39'20"N, 2°32'57"E). Measurements were made 0.8 m above and 10 m below the surface and were carried out from 3 to 8 July 1968.
Description of results
Deduced sediment transport directions The tidal ellipse appears to show a residual current to the southwest. Long-term measurements show that the strongest current is directed to the northeast on the west side of the bank and to the southwest on the east side of the bank.
Publication McCAVE (1979)
Time scale Meso scale (five days)
Space scale Meso scale (point measurement)

Method used Estimation of alongshore transport
Details on used methodology The theoretical alongshore sediment transport is obtained when multiplying the average suspended sediment concentration with the average alongshore current velocity. A number of processes are taken into account, which reduce significantly the theoretical computed sediment transport value.
Description of results Along the Dutch coast the average flow is assumed to be in northern direction with an average drift velocity of 3-5 cm/s. The computed average alongshore sediment transport amounts to 15 x 10^6 ton/year. After taking into account a number of processes such as the density influence on the vertical residual flow profile, the tide-induced residual transport, the effect of fluid mud flows, ... the computed value is reduced to 5 x 10^6 ton/year
Deduced sediment transport directions A net transport of 5 x 10^6 ton/year in the southern part of the coastal zone of Holland (Schouwen) and of 7. 5 x 10^6 ton/year in the northern part of the coastal zone (Noordwijk) takes place in a northern direction. The Flemish Banks would be responsible for an input of 1 to 2 x 10^6 ton/year in the Dutch waters.
Publication DRONKERS and MILTENBURG (1996)
Time scale Mega scale (years)
Space scale Mega scale (tens to hundreds of km)

Method used Current and sediment concentration measurements
Details on used methodology Four measuring frames were deployed on the dumping ground Zeebrugge East (east of Zeebrugge) in the period 14 Sept.-13 Oct. 2000. Two frames were equipped with acoustic doppler profiling sensors, measuring current velocity and direction and sediment concentration in cells of 0.5 m from the sea bottom to the water surface. Two frames were equipped with four optical backscatter sensors deployed on different heights in the water column; current velocity and direction were as well measured with a sensor near the bottom. The same four frames were deployed from 19 Dec. 2000 to 19 Jan. 2001 on the dumping ground S1 (west of Zeebrugge).
Description of results All frame measurements were analysed. A critical comparison between the doppler and the backscatter data was performed. The background turbidity and its relation to hydro-meteorological parameters (such as the impact of a storm) were analysed.
Deduced sediment transport directions The following net sediment (in suspension) transport rates were calculated: • For the dumping ground Zeebrugge East (mean value of 4 sites): during spring tide: 36 ton/m/tidal cycle during middle tide: 0 ton/m/tidal cycle during neap tide: 10 ton/m/tidal cycle • For the dumping ground S1 (mean value of 3 sites): during spring tide: 8 ton/m/tidal cycle during neap tide: 4 ton/m/tidal cycle All values refer to a direction of N80°E.
Publication MAGELAS (2001)
Time scale Macro scale (month)
Space scale Meso scale (point measurement)

Method used

Water samples (suspension measurements and grain size analysis)

Information on used method

Between December 1970 and September 1973 about 300 water samples of each 25 l have been taken in 25 points distributed over 5 sections parallel with latitude. The moment of sampling was not related to a particular tide or to a neap-spring cycle.

During January 1972 the suspended matter of the water samples of 20 different points was concentrated using a centrifuge. A grain size analysis was carried out on these samples. The analyses provided the grain size distribution of the mineral components and not of the floccules or aggregates.

Description of results

In every point the mean, maximum and minimum of suspended matter for the winter, the summer and for all measurement data has been calculated.

Deduced sediment transport directions

not available

Publication

GULLENTOPS et al. (1977)

Time scale

Micro scale for the individual measurements

Mega scale for the averaged suspended sediment concentration values (3 years)

Space scale

Meso scale (point measurement)

Mega scale for all results (BCP and further north towards Amsterdam)

Method used

Acoustical sand transport meter (ship-borne)

Information on used method

Every 10-20 min a vertical profile of current velocity (OTT meter), current direction (ELMAR-meter) and sand concentration and transport (AZTM) were measured in 16 points, situated on 3 different sections. Each section (consisting of 6 points) was measured during a different tidal cycle using 6 vessels. Measurements over the vertical were depending on water depth: 0.5, 1 and 2 m above bottom, 2, 4 or 8 m under surface.

Current velocity, direction and water elevation (OSM meters) have been measured during nearly 1 month in fixed position (many problems with instruments)

Description of results

In order to determine the discharge and the sand transport in the mouth of the Westerschelde a measuring section (from Zeebrugge to Westkapelle), consisting of three parts (A, B, C) was set up. Total transport has been calculated every 20 minutes in every point. The following table gives location and tidal information (mean spring tidal coefficient at Vlissingen is 1.157, ST = spring tide, MT = mean tide).

Point	Section	UTM Northing	UTM Easting	Day measurement	Tidal coefficient
1	A	5691476	513136	1/1/92	1.102-ST
2	A	5692495	513030	1/1/92	1.102-ST
3	A	5693549	512976	1/1/92	1.102-ST
4	A	5694486	512939	1/1/92	1.102-ST
5	A	5695464	512902	1/1/92	1.102-ST
6	A	5696260	512940	1/1/92	1.102-ST
6	B	5696220	512822	3/21/93	1.106-ST
7	B	5698112	514673	3/21/93	1.106-ST
8	B	5699967	516416	3/21/93	1.106-ST
9	B	5701840	518296	3/21/93	1.106-ST
10	B	5703761	520074	3/21/93	1.106-ST
11	B	5705574	521792	3/21/93	1.106-ST
11	C	5705557	521799	9/17/92	1.072-MT
12	C	5706229	523672	9/17/92	1.072-MT
13	C	5706911	525563	9/17/92	1.072-MT
14	C	5707985	528346	9/17/92	1.072-MT
15	C	5708212	528905	9/17/92	1.072-MT
16	C	5708607	529953	9/17/92	1.072-MT

Deduced sediment transport directions

not available

Publication

RWS (1993a); RWS (1993b); RWS (1993c), VAN DEN EYNDE (1999a)

Time scale

Micro scale:1 tidal cycle: 17/09/1992 (mean tide), 01/10/1992 (spring tide), 21/03/1993 (spring tide)

Space scale

Meso scale (point measurement)

Method used

Aeroplane multi-spectral scanner registrations

Water samples (suspension measurements)

Information on used method

On five moments during one tidal cycle (spring tide) surface (upper 1 m) suspended sediment concentration measurements were carried out along the whole Belgian coast (resolution of 15 m) using an aeroplane multi-spectral scanner. Simultaneously surface sediment samples (1.2 m under surface) have been taken from vessels in order to calibrate the aeroplane scanner registration.

Description of results

The suspended sediment concentration data have been combined with the results of a high resolution 2D hydrodynamic model (75 m x 75 m) of the same zone in order to calculate the suspended sediment transport during the measured tidal cycle in the entire Belgian coastal zone. The sediment concentration was supposed to be constant over the vertical. In the following table the suspended sediment transport in 7 sections perpendicular to the coastline is presented. The transport is integrated over flood and ebb respectively and has been divided by the length of the section (about 7 km).

Section	Location	Ebb-transport (kg/m)	Flood-transport (kg/m)	Residual transport (+ eb, - fl)
1	mouth of Yser	460	1239	-779
2	harbour Oostende	2628	3524	-896
3	bend in coast at Wenduine	4321	4608	-287
4	W-breakwater Zeebrugge	4409	4009	400
5	E-breakwater Zeebrugge	3991	5237	-1246
6	Knokke	2202	4682	-2480
7	Zwin	1398	4927	-3529

Deduced sediment transport directions

The residual transport is parallel to the coast and flood-dominated (towards NE), except in section 4.

Publication

EUROSENSE (1994a)

Time scale

Micro scale (1 tidal cycle: 10/07/1991 (spring tide))

Space scale

Mega scale (Belgian coastal zone: 70 km x 7 km)

Method used

Optical sensors

Information on used method

Measurements consisted of water elevation (Aanderaa WLR 7S tide meter), current velocity and direction (Aanderaa RCM7) and wave height (non–directional wave rider buoy). During the campaign water was pumped up from two bottom frames with each 5 pumps (mounted at 0.25, 0.5, 0.75, 1.0 and 1.25 m above bottom) and from the measuring container (1 m under water surface) and circulated in tubes into a nearby measuring container installed in between the two locations. Every 15 minutes the seawater from one of the tubes was measured using 3 Partech sensors placed in line (IR 100CI, IR 40CL, IR 15CL) in order to determine sand and total sediment concentration. The sensors have been calibrated in a laboratory using sand and mud from the harbour of Zeebrugge.

Description of results

The measurements aimed at studying the sediment transport near the harbour of Zeebrugge. There the currents are strongly influenced by the harbour dams. In the following table the total transport per ebb and flood of all the sediment and the (sand)-part is presented for a spring tide (ST: 09/02, 21h36 – 10/02, 10h06), a mean tide (MT: 12/02, 23h54 – 13/02, 12h26) and a neap tide (NT: 15/02, 14h46 – 16/02, 03h37).

Site	UTM Northing	UTM Easting	Tidal Phase	Flood (t/m)	Ebb (t/m)
Frame W	5689550	516425	ST	20.3 (6.8)	10.1 (3.1)
			MT	11.9 (3.3)	9.6 (3.5)
			NT	4.5 (1.0)	1.5 (0.7)
Frame E	5689550	517315	ST	8.0 (2.3)	17.0 (3.7)
			MT	6.2 (1.4)	7.7 (1.7)
			NT	1.4 (0.04)	0.9 (0.1)
Tide meter	5689375	517160			
Wave rider	5690000	517500			
Curr. Meter W	5689700	516375			
Curr. Meter E	5689550	517365			
Container	5689625	516870			

Deduced sediment transport direction

Spring tide (09/02, 21h36 – 10/02, 10h06). Frame W: flood dominated transport towards SE. Frame E: ebb dominated transport towards NW

Mean tide (12/02, 23h54 – 13/02, 12h26). Frame W: flood dominated transport towards SE, ebb transport towards NE is small. Frame E: flood and ebb transport are similar

Neap tide (15/02, 14h46 – 16/02, 03h37). Frame W: flood dominated transport towards SE, ebb-transport towards NW is small. Frame E: flood and ebb transport are similar

Publication

EUROSENSE (1994b); BLOMME et al. (1993)

Time scale

Meso scale: 7 days from spring to neap tide: 09/02/1993 – 16/02/1993

Meso scale: 2 days during a storm: 18/02/1993 – 20/02/1993

Space scale

Meso scale (point measurement)

Method used

Optical sensors

Information on used method

Measurements consisted of water elevation (Aanderaa WLR 7S tide meter), current velocity and direction (NBA-DNC2B) and wave height (non–directional wave rider buoy). During the campaign water was pumped up from two bottom frames with each 5 pumps (mounted at 0.25, 0.5, 0.75, 1.0 and 1.25 m above bottom) and from the measuring container (1 m under water surface) and circulated in tubes into a nearby measuring container installed on the shore. Every 15 minutes the sea water from one of the tubes was measured using 3 Partech sensors placed in line (IR 100CI, IR 40CL, IR 15CL) in order to determine sand and total sediment concentration. The sensors have been calibrated in a laboratory using sand and mud from the harbour of Zeebrugge.

Description of results

The aim of the measurements was to study the influence of the shoreface in transporting sand towards the Het Zwin. The results show that the sediment transport and direction are influenced by waves and by the nearby groyne. In the following table the total transport of all the sediment and the (sand)-part is presented for a neap tide (NT: 01/04, 15h20 – 02/04, 04h20), a mean tide (MT: 05/04, 20h00 – 05/04, 09h50) and a spring tide (ST: 07/04, 21h10 – 08/04, 09h50) during calm conditions (significant wave height < 0.5 m).

Site	UTM Northing	UTM Easting	Tidal Phase	Flood (t/m)	Ebb (t/m)
Frame W	5691113	524442	NT	1.0 (0.03)	1.7 (0.07)
			MT	5.5 (0.4)	4.7 (0.3)
			ST	5.4 (0.4)	6.9 (0.3)
Frame E	5691182	524630	NT	1.1 (0.03)	1.9 (0.09)
			MT	7.0 (0.5)	6.5 (0.4)
			ST	5.8 (0.4)	7.5 (0.4)
Tide meter	5691080	524400			
Wave rider	5691235	524500			
Curr. Meter W	5691100	524393			
Curr. Meter E	5691182	524630			
Surface pump	5691150	524535			

Deduced sediment transport directions

Significant wave height <0.5 m: residual sediment transport is longshore and ebb-dominated (towards W), cross-shore transport components are very small.

Significant wave heights 0.8-1.2 m: sediment transport is twice as much as during calm weather conditions, residual transport direction is towards NE, cross-shore transport component is important.

Publication

EUROSENSE (1994c)

Time scale

Meso scale (7 days from neap to spring tide: 01/04/1993 – 08/04/1993)

Space scale

Meso scale (point measurement)

Method used

Optical backscatter sensors (shipborne)
Water samples (total suspension, Chl-a and Phaeopigments)

Information on used method

Ship-borne measurements were carried out in the coastal zone east of Oostende to measure the sediment transport (mud) during a tidal cycle. The instrumentation consists of NBA-DNC3 and ADCP-RDInstrument (1200 kHz shallow water, range 20 m, bin size 1 M) to measure current velocity and direction; a rosette on SCTD SBE09 SeaBird system + 1 OBS + Niskin-bottles which is kept at about 3 m above the bottom. Every 20 minutes a Niskin-bottles is closed and the water sample is analysed for total suspended matter, Chl-a and phaeopigments; a SCTD SBE19 SeaBird system + 1 OBS which is kept at about 3 m under the surface and a SCT SBE21 SeaBird system is permanently installed in the sea water intake of the R/V Belgica. Water depth measurements are carried out using a DESO-20, corrected with a TSS 320B swell compensator. The analysed data of total suspended matter are used to calibrate the OBS.

Description of results

Location and tidal information of measurements are given in table below:

Belgica Camp. Nr	Start date + time	End date + time	UTM Northing	UTM Easting	Tidal Coef.
98/08	16/04/98 18h26	17/04/98 07h50	5699209	503406	1.139-ST
98/14a	08/06/98 16h05	09/06/98 04h00	5700061	502930	1.013-MT
98/14b	09/06/98 15h30	10/06/98 04h15	5682081	496839	1.057-MT
98/17a	26/08/98 16h10	27/08/98 05h15	5681895	496989	1.135-ST
98/17b	27/08/98 12h40	28/08/98 02h00	5681896	496862	1.052-MT
99/07	08/03/99 15h47	09/03/99 05h03	5682730	496363	0.873-NT
99/17	13/07/99 06h20	13/07/99 19h20	5698150	486676	1.171-ST
00/08	21/03/00 10h14	21/03/00 23h07	5693049	518209	1.179-ST
00/14	29/05/00 08h53	29/05/00 22h01	5692818	515635	0.834-NT
00/19	10/07/00 09h15	10/07/00 22h22	5700914	503555	0.783-NT
00/26	23/10/00 20h10	24/10/00 08h53	5693314	503653	0.913-MT
00/31	07/12/00 10h00	08/12/00 05h16	5696814	518705	0.888-MT
01/01	25/01/01 11h45	26/01/01 00h26	5702140	515143	0.995-MT
01/06b	07/03/01 16h07	08/03/01 09h38	5691672	509234	1.016-MT
01/06b	08/03/01 10h41	09/03/01 06h29	5688809	501428	1.097-MT
01/17a	18/06/01 18h20	19/06/01 07h15	5698187	527355	0.937-MT
01/17b	19/06/01 19h14	20/06/01 09h06	5706651	510190	1.041-MT

Deduced sediment transport directions

not available

Publication

BACKERS et al. (1999), BMM (2001a); BMM (2001b); BMM (2001c), VAN DEN EYNDE (1999a)

Time scale

Micro scale (1 tidal cycle)

Space scale

Meso scale (point measurements)

Method used Optical backscatter sensors (towfish) Acoustical backscatter (hull mounted ADCP) Water samples (suspension measurements)
Information on used method Measurements during a tidal cycle were carried out across the access channel near the entrance of the harbour of Zeebrugge using the vessel Oostende XI on 19/04/2000 (09h10-21h23) and 26-27/04/2000 (02h38-15h15) in order to determine the sediment transport going in and out of the harbour. A towfish (Navitracker) equipped with 2 OBS sensors measured optical backscatterance, pressure and position. The OBS's were calibrated with sludge taken from the survey area and with the analysed water samples. A hull-mounted Acoustic Doppler Current Profiler (Nortec AS 1.5 MHz, type VM-NDP) measured current speed, direction and acoustical backscatterance. The acoustical backscatter signal was converted into turbidity using the OBS data.
Description of results Spring tide of 19/04/2000: $46x10^6$ m^3 water and 9200 t sediment into the harbour; $44x10^6$ m^3 water and 6000 t out of the harbour. Neap tide of 26-27/04/2000: $33.3x10^6$ m^3 water and 2050 t sediment into the harbour; $32.8x10^6$ m^3 water and 1260 t out of the harbour.
Deduced sediment transport directions 3200 t of mud flowing into harbour during spring tide and 795 t during neap tide. Measurements were carried out during good weather. The results are probably underestimating the transport because no measurements are available for the lowest 2 m, in this bottom layer the mud concentration and thus the transport could be very high.
Publication CLAEYS (2000), CLAEYS et al. (2001)
Time scale Micro scale (1 tidal cycle)
Space scale Macro scale (0.7 km track: perpendicular to access channel near entrance of Zeebrugge harbour)

Method used Optical backscatter sensors (bottom frame) Acoustical backscatter (bottom mounted ADCP)
Information on used method During two periods of each 30 days a number of parameters have been monitored in the vicinity of the dumping place B/6 using four fixed measuring systems (bottom frame) in order to determine the influence of dumping of dredged matter on the sediment transport (mud). Two different type of configurations were used: A bottom frame with one OBS, CT-sensor, current meter and 3 OBS's attached along a rope connected to a buoy. A bottom frame with a CTD sensor, current meter, 2 OBS's placed in the vicinity of a bottom frame with an ADCP.
Description of results The dumped matter from the harbour of Zeebrugge on B/6 behaves as a cloud of higher density at 1.5 m above the bottom; the influence is limited in the horizontal plane to 1.5 km. The calculated residual sediment
Deduced sediment transport directions 01/10/2000-13/10/2000: residual sediment (mud) transport is towards E (parallel with coast) and amounts to 42150 t/day or 15.38x10^6 t/yr. The mud dumped on B/6 (3.03x10^6 t/yr) forms thus only 20% of the total sediment (mud) transport on this dumping site.
Publication VAN PARYS and PIETERS (2001)
Time scale Macro scale (1 month: 13/03/2000-12/04/2000 and 14/09/2000-13/10/2000)
Space scale Meso scale (point measurement)

Method used

Optical backscatter sensors
Acoustical backscatter sensors
Total sediment load sampler

Information on used method

The measurements are part of the Mast-RESECUSED project and aimed at studying the resuspension of sediment on the Middelkerke Bank. Two measuring frames were placed in the central part of the bank and were deployed during two periods, one of 16 day (27/04–13/05/1991) and one of 40 days (04/03–13/04/992). The frames contained: a pressure sensor, an altimeter, two inclinometer, a compass, 2 ElectroMagnetic Current meter (EMF Delft Hydraulics) mounted at 0.25 m and 0.50 m above the bed, 2 OBS (D&A) mounted at 0.15 and 0.25 m above the bed. Ship-borne current measurements during one tide were carried out in 3 stations near the frames during their deployment in March 1992 and on 4 stations in April and July 1992.

Measurements of suspended sediment load and hydrodynamics were done in two positions (G6, G7) during 3-4 days (20-23/07/1992) using the Total Sediment-Load Sampler (TSLS, Delft Hydraulics). The frame contained: 3 ABS (UEA Acoustic Backscatter Sensor Instrument), 4 current meter (Ott propeller meter), an EMC meter, a vertical array of suction samplers and a bedload sampler

Description of results

F1 and F2 sites: Residual circulation was difficult to measure because the magnitude is close to the accuracy of the current meter. Measurements of suspended load were difficult because of ambiguous interpretation of OBS signal. G6 and G7 sites: the suspended transport rates are very small. In table are shown the locations and deployment periods as well as some results.

Site	Start	End	UTM Northing	UTM Easting	Critical suspension shear stress	Suspended transport rates / tide
F1a	4/27/91	5/13/91	5685673	482312	na	na
F2a	4/27/91	5/13/91	5685082	482969	na	na
F1b	3/4/92	4/13/92	5685583	482353	na	na
F2b	3/4/92	4/13/92	5685054	483031	na	na
G6	7/20/92	7/23/92	5679570	478222	4 Pa	negligeable
G7	7/21/92	7/23/92	5681918	480363	12 Pa	1.5 kg

Deduced sediment transport directions

not available

Publication

DE MOOR and LANCKNEUS (1993), STOLK (1993), VINCENT and STOLK (1993)

Time scale

Macro scale
2 weeks: 27/04/1991 – 13/05/1991
5 weeks: 04/03/1992 – 13/04/1992
3-4 days: 20-23/07/1992

Space scale

Meso scale (point measurements)

Method used

Optical Backscatter sensors
Profiling Acoustic Backscatter sensor

Information on used method

During two periods (16/02-29/03/1994, 18/01–08/03/1995) sediment transport measurements were carried out along the Middelkerke Bank using two bottom frames (Suske & Wiske) (EU-MastII-STARFISH). During the first period the frames were deployed on both sides of the bank, during the second period they were moored on the central and southern part of the NW flank of the bank. Simultaneously with the frame measurements moored current meter measurements were done at two stations. The frames were equipped with 2 EMC (EMF, Delft Hydraulics) mounted at 0.25 m and 0.50 m above the bed, 2 OBS (D&A) mounted at 0.15 m and 0.25 m above the bed, a profiling ABS with 2 sensors mounted at 0.75 m above the bed, a pressure sensor, compass, inclinometer.

Description of results

Results are only present for deployments of 1995, during 1994 the ABS data logger measured only during 15 days (S94) and 6 days (W94). The interpretation of data from OBS and electromagnetic current meter is complex because of variation in bed position due to bed form migration. Vincent et al. (1998) report the results from the ABS:

Location	Easting (m)	Northing (m)	Timestamp (UTC)	Flux 0-0.3m (tonnes/m/day)	Flux to surface (tonnes/m/day)	Direction (°)	Susp. size max (mu)	Bed size mode (mu)
S94	482306	5685570	1994-02-16 1994-03-29	-	-	-		
W94	483010	5685029	1994-02-16 1994-03-29	-	-	-		
S95 (station 3)	478533	5679253	1995-01-18 1995-03-08	0.05	0.1	52	140-200	180-212
J95 (station 1)	482415	5685554	1995-01-18 1995-03-08	0.9	1.22	51	100-140	250-300, 425-500

Deduced sediment transport directions

The residual transport direction is similar to strongest current direction; this is 25° obliquely to the axis of the bank at the NW-flank (50°) and towards the SE on the SE-flank.

Publication

STOLK et al. (1996), VINCENT et al. (1998)

Time scale

Macro scale (49 days (18/01–08/03/1995)

Space scale

Meso scale (point measurement)

Asymmetry of bedforms

Tracers

Suspension measurements

STA

Models

Others

Method used Profiling Acoustic Backscatter Sensor
Information on used method Hydrodynamic and wave measurements took place during the Mast2-CSTAB project on the Middelkerke Bank between 25-28/02 using a bottom frame (STABLE II). The instrumentation on the STABLE II frame was equipped with pairs of orthogonal ECM (used to measure tidal and wave-induced currents), pressure transducer, profiling ABS (vertical resolution of 1 cm). Deployment frame with shear stress meter (SSM) plate used to measure horizontal and vertical flow components, pressure sensor, pressure difference meter, two inclinometers and a compass.
Description of results The aim of the STABLE II and SSM was to measure high frequency small-scale processes (SPM, drag and shear stress over bedforms).
Deduced sediment transport directions not available
Publication O'CONNOR (1996), WILLIAMS (2000)
Time scale Smaller than micro scale (1-2 seconds)
Space scale Micro scale (0.5 m^2 (ripples))

Method used Optical Backscatter Sensors
Information on used method During the MAST2_CSTAB project field experiments took place between 17/02/1994 5/03/1994 on the intertidal zone of the Nieuwpoort beach, which is nearby to the Middelkerke Bank. From the four stations only the outer stations 3 & 4 were equipped with OBS. The instrumentation used was: electromagnetic current meters (800 2-axis Valeport), OBS-1 (D&A), pressure transducers, TOSCA tripode (3 D&A OBS, 4 Valeport EMC, pressure sensor), X-band radar to measure wavelength scales and directions, magnetic and fluorescent tracers to measure sand movements.
Description of result
Deduced sediment transport directions The mean cross-shore flows were found to be offshore near the seabed but directed onshore in the water column (undertow current). Longshore flows are tidally dominated and flow towards the northeast
Publication O'CONNOR (1996), HUNTLEY and MACDONALD (1996), VOULGARIS and SIMMONDS (1996)
Time scale Micro scale (tidal cycle)
Space scale Macro scale (200 m x 375 m)

Method used
Satellite images

Details on used methodology
The most important satellites that are used to determine the concentration of suspended matter are SeaWifS, NOAA AVHRR and ERS1 ATSR. SeaWifS takes 1 photo every day, AVHRR 4 photos every day. Every year about 20-30 SeaWifS and 40-50 AVHRR photos are usable for the BCS. While an indication of spatial distributions of suspended sediments (and sea surface temperature) can be obtained from the NOAA AVHRR and the ERS1 ATSR sensors, their use is limited by the lack of multi-spectral data at visible wavelengths. The multi-channel SeaWifs data are valuable in allowing discrimination between the contributions of chlorophyll content, gelbstoff and inorganic suspended particulate matter.

Description of results
An inventory of processed SeaWifs images can be found on the website http://www.mumm.ac.be/OceanColour/SeaWiFS_TSM/index.htm). The picture show the surface suspended matter.

Deduced sediment transport directions
not available

Publication
RUDDICK et al. (1998); RUDDICK et al. (2000), VAN DER WOERD et al. (2000)

Time scale
Micro scale (for one picture at one given moment)
Mega scale (compilation of different pictures)

Space scale
Mega scale (Southern North Sea)

Method used

2D sediment transport model (suspended load)

Information on used method

The 2D sediment transport model (mu-STM) is a semi-Lagrangian model that is based on the Second Moment Method (de Kok, 1994). The model simulates advection and diffusion of suspended matter under the influence of tidal currents and of the currents generated by the waves (Stokes drift). The bottom stress is calculated with an adapted formula of Bijker (Van den Eynde & Ozer, 1993). The erosion and deposition is modelled according to Ariathurai-Partheniades (Ariathurai, 1974) and Krone (1962).

The model is applied to a rectangular zone on the BCS (51°00, 2°05' - 51°38', 3°35'); the grid size is 750x750 m^2. A 2D hydrodynamic model of the same area provides the hydrodynamic data. The boundary conditions (suspended sediment concentration) are based on averaged suspension measurements. The initial condition represents the amount of mud (%) on the sea floor; the erosion resistance of the mud increases with depth under the sea bottom. Dumping is simulated.

Description of results

This model was developed in the framework of the SEBAB-project to simulate the suspended sediment transport on the BCS, to examine the different sources of mud and to set up a sediment balance for mud. The high concentration of SPM in the coastal zone is a secondary phenomenon, which is caused by the decreasing water depth and the steadily decreasing residual water transport from the southwest towards the northeast. The mud balance based on model simulations results is presented in the table below.

	million tons/year
Input	
W-boundary (Strait of Dover)	+11.4
Westerschelde	+1.8
Mud in suspension	+0.3
Erosion of parent bed	+5.4
Total Input	+18.9
Deposition	
Navigation channels	-0.5
Rest of model area	-1.7
Total Deposition	-2.2
Output	-16.7

Deduced sediment transport directions

Residual suspended sediment transport is highest in the coastal zone and is directed from the southwest towards the northeast. The magnitude is decreasing towards the northeast and is reaching a minimum off Zeebrugge, further towards the northeast the magnitude is increasing.

Publication

FETTWEIS and VAN DEN EYNDE (2000a; 2000b; 2001a; 2001b)

Time scale

1 year

Space scale

100 km x 40 km, i.e. map 'Vlaamse Banken'

Method used 2D sediment transport model (suspended load)
Information on used method The 2D sediment transport model (mu-STM) is a semi-Lagrangian model that is based on the Second Moment Method (de Kok, 1994). The model accounts for 3 different sediment classes (sand, fine sand and mud) and calculates for each of them advection and diffusion of suspended matter under the influence of tidal currents and of the currents generated by the waves (Stokes drift). The bottom stress is calculated with an adapted formula of Bijker (Van den Eynde & Ozer, 1993). The erosion and the deposition are modelled according to Ariathurai-Partheniades (Ariathurai, 1974) and Krone (1962). The model is applied to a rectangular zone on the BCS (51°00, 2°05' - 51°38', 3°35'); the grid size is 750x750 m². A 2D hydrodynamic model of the same area provides the hydrodynamic data.
Description of results The objective of the VESTRAM-project was to calibrate and validate the sediment transport model using measurements and to formulate recommendations for the management of dumping of dredged matter. In order to achieve the latter, 6 different types of simulations (with and without wind forcing and/or waves) for the 3 different sediments have been carried out in order to simulate the effects of dumping in 78 different points, distributed over the grid. During every simulation 500 tons of sediment were dumped and followed during 28 days. The main conclusions are: Most of the sand stays on the dumping places. The fine sand is transported towards the east and stays on the Vlakte van de Raan, off Walcheren and 30 km off the coast. The effect of wind from the south is that the fine sand is transported further away form the coast, whilst during northern winds the fine sands comes closer to the coast. Waves increase the dispersion of the fine sand. Mud is quickly distributed and is concentrated in two high turbidity zones, one close to the coast between Zeebrugge and Oostende and the other one between Zeebrugge and the mouth of the Westerschelde. Mud that is dumped more than 30 km off the coast is leaving quickly the model domain. Without wind forcing no transport towards the coast occurs.
Deduced sediment transport directions Residual sediment transport direction for fine sand and mud is towards the northeast.
Publication VAN DEN EYNDE (1995; 1997; 1998; 1999a; 1999b); VAN DEN EYNDE and RUDDICK (1998)
Time scale 1 month
Space scale 100 km x 40 km, i.e. map 'Vlaamse Banken'

Method used 3D sediment transport model (suspended load)
Information on used method The 3D sediment transport model (SLIB3D) is semi-Lagrangian and is based on the Second Moment Method (de Kok, 1994). The grid extends over an area of 70 km along the Dutch coastal zone, is curvilinear with a grid size decreasing towards the coast. The boundary conditions (suspended sediment concentration) are based on averaged suspension measurements.
Description of results The objective of the study is to simulate the mud transport in the Dutch coastal zone for the present situation and after construction of the 'Maasvlakte Noord'. Three different scenarios have been simulated: southwest wind and storm, northwest storm and northeast wind. This choice is based on the assumption that relatively short storm periods are responsible for an important part of the yearly mud transport.
Deduced sediment transport directions The residual mud transport during normal conditions (southwest winds of 4.5 m/s) is towards the northeast and amounts to 3.1×10^7 kg/tide (22×10^6 tonnes/year) through a section near Walcheren. Other data are only given for the section 'Ter Heijde' located near the mouth of the Meuse. These situations are calculated for a duration of a storm of 2 days, followed by 10 days of normal condition (southwest winds of 4.5 m/s): After 2 days of SW-storm (wind of 15 m/s) the mud flux is 1.4×10^8 kg/tide towards the northeast. After 2 days of NW storm (wind of 15 m/s) the flux is still towards the northeast, but reduces to 3.0×10^7 kg/tide During normal wind conditions (5 m/s) from the northeast the mud flux reduces to 4.6×10^6 kg/tide (3×10^6 tonnes/year) and is directed towards the southwest.
Publication SALDEN (1998)
Time scale 100 days
Space scale 70 km coastal zone between Oostende and Ameland

Method used 2D residual circulation model
Information on used method Averaging the solution of hydrodynamic equations provides residual currents with 100% error. In the proposed model therefore the hydrodynamic equations are averaged over a time T and the resulting steady-state equations are solved. The contribution of long-wave motions is eliminated in the linear terms but dominated the non-linear terms, which constituted an additional forcing, called the 'tidal stress'.
Description of results The results of the model revealed the existence of a secondary gyre off the Belgian coast, which explained several observations concerning the mud deposition in the Southern North Sea, in particular: A southerly long-shore current off the Northern Belgian coast. An extended tongue of highly turbid water (>0.1 g/l) spreading northeasterly from the Scheldt estuary. Accumulation of mud along the northeastern part of the coast.
Deduced sediment transport directions The suspended sediment transport direction is towards the northeast except off the Northern Belgian coast, where the direction is towards the southwest. (Remark: the modelling applies to a situation before the extension works of the Harbour of Zeebrugge (1977-1986))
Publication NIHOUL (1975), NIHOUL and GULLENTOPS (1976); NIHOUL and ADAM (1975)
Time scale Months
Space scale Southern bight of the North Sea

Method used 2D sediment transport model (total load)
Information on used method The sediment transport is modelled under influence of tides and waves using the transport formula of Ackers & White. The bottom friction is calculated in every grid cell using Bijker's formula. In every grid cell the percentage of exceedance of transport is determined for the considered sediment classes. By doing so areas can be identified were the percentage of exceedance of transport is high or low. An area with a high exceedance indicates that the matter of that sediment class is for the greater part transported elsewhere, in case of a low exceedance, the probability is high to find most of the sediments belonging to this class in that area. The model is applied to a rectangular zone on the southern Bight of the North Sea (grid cell 7.5x7.5 km^2)
Description of results The results show the importance of wave effects in calculating the sediment transport. In the results a tendency of accumulation of the fine sediments in the northern parts of the grid is indicated.
Deduced sediment transport directions The averaged sediment transport direction is towards the north.
Publication VAN DEN EYNDE and OZER (1993)
Time scale 1 month
Space scale Southern bight of the North Sea

Method used 2D sedimentation/erosion model
Information on used method The sedimentation and erosion is studied using the erosion energy and the erosion stress parameter as a function of the depth averaged currents (provided by a 2D hydrodynamic model). The model is applied to a rectangular zone on the BCS (51°00, 2°05' - 51°38', 3°35'). The model is based on the assumption that in areas with an energy minimum the suspended particles have a greater probability to settle down and the sediment layer has a low probability of being eroded. On the contrary, where the energy is maximum, the probability of erosion is high.
Description of results The model was used to study the impact of the future expected increase of sand extraction in the region of the Flemish Banks and off the harbour of Zeebrugge. The results show that the sandbanks are characterised by local maxima of energy, but that other maxima appear either close to the banks or even not tighten with the general bank structure. Also the swales like the Westdiep, the Scheur and the Oostgat are places with higher energy.
Deduced sediment transport directions The western sandbanks show a distribution of erosion stress vectors that generally turn around the head of the banks inducing that material eroded from the banks tend to rotate around them. In the coastal zone the stress vectors are directed northeastward, i.e. in the direction of the residual tidal circulation. In the regions influenced by the Scheldt estuary the stress is directed northward along Walcheren or northwestward along the Scheur.
Publication ADAM et al. (1981); DJENIDI and RONDAY (1984)
Time scale yearly averaged
Space scale 100 km x 40 km, i.e. map 'Vlaamse Banken'

Method used 2D sediment transport (total and suspension load)
Information on used method The model is used to investigate the broad trends of the seabottom evolution. The relationship between the transport and the fluid velocity is derived from field measurements and stands under the form of a bulk formula including the bed load and the suspension mode. The modelling of the total transport is based on the hypothesis that the bed load transport exists only in a quasi laminar layer and that suspension transport occurs from above this layer towards the surface. The suspension transport is described by a transport equation of sediment concentration. The bedload transport is calculated using a sediment conservation equation of the type Peter-Meyer & Müller (1949) extended by a term calculating the vertical exchange with the water column where the suspension transport occurs. The hydrodynamics are calculated using a 2D hydrodynamic model. The model is applied to the eastern Belgian coast and has a grid size of 500 x 500 m^2.
Description of results Long-range simulations (15 years) are presented for different configurations of the coastline in the eastern Belgian coastal zone. The initial condition used the bathymetry of 1976, two configurations are considered: one before and one after the construction of the new outer port of Zeebrugge. Dredging is taken into account. Comparison of both situations indicates that there is a general tendency of sedimentation of up to 2.5 m after 15 years. Erosion occurs much more locally and is concentrated around the breakwaters of the new port. The comparison of both simulations shows that the new outer port has an important influence on the sediment dynamics: two sedimentation zone are visible, one off Heist and another between Blankenberge and Zeebrugge.
Deduced sediment transport directions not available
Publication DJENIDI and RONDAY (1992)
Time scale 15 years
Space scale 30x15 km^2: eastern Belgian coastal zone between De Haan and Kadzand

Method used

Optical backscatter sensors (ship-borne)
Water samples (total suspension, Chl-a and Phaeopigments)

Information on used method

Ship-borne measurements were carried out in the coastal zone east of Oostende to measure the sediment transport (mud) during a tidal cycle. The instrumentation consists of NBA-DNC3 and ADCP-RDInstrument (1200 kHz shallow water, range 20 m, bin size 1 M) to measure current velocity and direction; a rosette on SCTD SBE09 SeaBird system + 1 OBS + Niskin-bottles which is kept at about 3 m above the bottom. Every 20 minutes a Niskin-bottle is closed and the water sample is analysed for total suspended matter, Chl-a and phaeopigments; a SCTD SBE19 SeaBird system + 1 OBS which is kept at about 3 m under the surface and a SCT SBE21 SeaBird system is permanently installed in the sea water intake of the R/V Belgica. Water depth measurements are carried out using a DESO-20, corrected with a TSS 320B swell compensator. The analysed data of total suspended matter are used to calibrate the OBS.

Description of results

Location, tidal information, SPM transport per tide and direction are given in table below:

Belgica Camp. Nr	Start date + time	End date + time	UTM Northing	UTM Easting	Tidal Coef.	Tide (t/m)	Direction
98/08	16/04/98 18h26	17/04/98 07h50	5699209	503406	1.139-ST		
98/14a	08/06/98 16h05	09/06/98 04h00	5700061	502930	1.013-MT		
98/14b	09/06/98 15h30	10/06/98 04h15	5682081	496839	1.057-MT		
98/17a	26/08/98 16h10	27/08/98 05h15	5681895	496989	1.135-ST		
98/17b	27/08/98 12h40	28/08/98 02h00	5681896	496862	1.052-MT		
99/07	08/03/99 15h47	09/03/99 05h03	5682730	496363	0.873-NT	4.01	NE (58°)
99/17	13/07/99 06h20	13/07/99 19h20	5698150	486676	1.171-ST	1.62	NE (32°)
00/08	21/03/00 10h14	21/03/00 23h07	5693049	518209	1.179-ST	27.78	N (8°)
00/14	29/05/00 08h53	29/05/00 22h01	5692818	515635	0.834-NT	4.14	NE (45°)
00/19	10/07/00 09h15	10/07/00 22h22	5700914	503555	0.783-NT	0.29	E (85°)
00/26	23/10/00 20h10	24/10/00 08h53	5693314	503653	0.913-MT	3.8	W (273°)
00/31	07/12/00 10h00	08/12/00 05h16	5696814	518705	0.888-MT	1.54	W (273°)
01/01	25/01/01 11h45	26/01/01 00h26	5702140	515143	0.995-MT	2.07	SE (121°)
01/06b	07/03/01 16h07	08/03/01 09h38	5691672	509234	1.016-MT	7.22	N (7°)
01/06b	08/03/01 10h41	09/03/01 06h29	5688809	501428	1.097-MT	8.74	NNW (310°)
01/17a	18/06/01 18h20	19/06/01 07h15	5698187	527355	0.937-MT		
01/17b	19/06/01 19h14	20/06/01 09h06	5706651	510190	1.041-MT		

Deduced sediment transport directions

The highest SPM transports are situated between Oostende and the B/NL border and on the Vlakte van de Raan. In the coastal zone the maximum transport vectors are NE (flood) and SW (ebb) directed. Residual transport directions (see table) are variable and depending on local conditions during the measurements. The tidal residual water transport (m/s) patterns are more regular and are directed towards the NE (variations between N5°-N85°).

Publication

BACKERS et al. (1999); BMM (2001a; 2001b; 2001c); VAN DEN EYNDE (1999a), FETTWEIS and VAN DEN EYNDE (2001b)

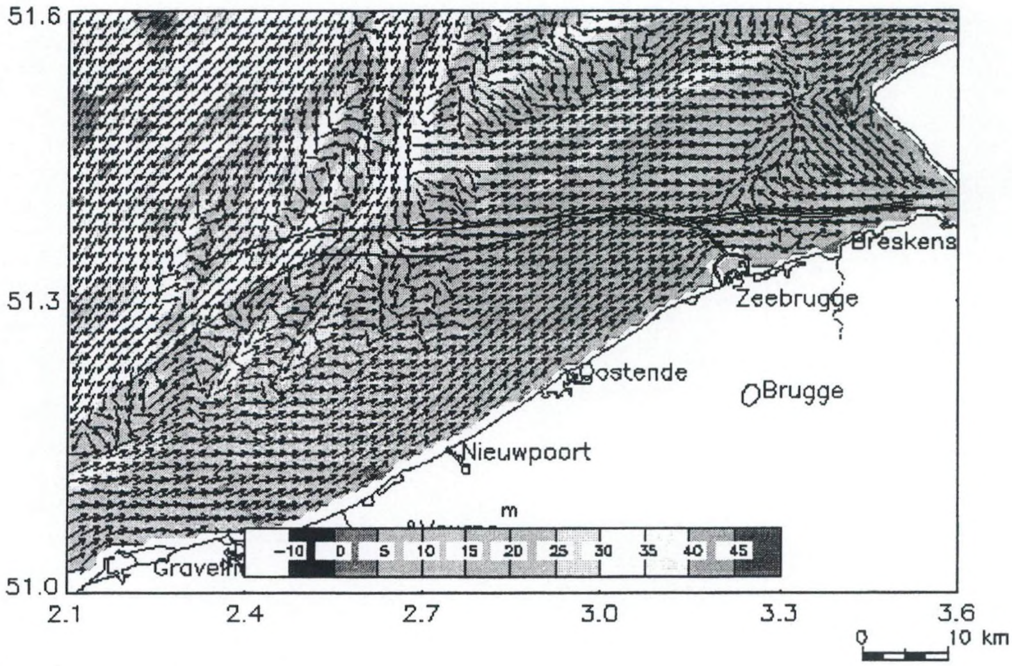
Time scale

Micro scale (1 tidal cycle)

Space scale

Meso scale (point measurements)

Method used
2D sediment transport model (total load)
Information on used method
The model (mu-SEDIM) is based on a local total load formula in each grid point. The bottom stress is calculated under the currents and waves and accounting for the roughness in the grid point, using a 2D hydrodynamic and a 2nd generation wave model. This total roughness is calculated from the median grain size and from the calculated ripple height and steepness and the calculated bottom load. A total load sediment transport formula (Ackers and White) is used to calculate the sediment transport vectors. The simulations are executed for the year 1999.
Description of result
The figures show the transport vectors and (in colour) the bathymetry (m).



Transport vectors

Deduced sediment transport directions
The sediment transport on the sandbanks is in a clockwise direction: to the northeast on the W flank of the banks and southwest directed on the E flank of the bank. In the coastal zone (20 km) the transport direction is towards the northeast. In the Scheur, the direction is towards the west. In open sea (north of the sandbanks) the sediment transport direction is towards the southwest.
Publication
VAN DEN EYNDE (2001)
Time scale
1 year
Space scale
100 km x 40 km, i.e. map 'Vlaamse Banken'

Method used Hyperspectral remote sensing in combination with in-situ depth measurements.
Information on used method By means of imaging spectroscopy, it is aimed at distinguishing between the different sand types occurring along the Belgian coast. Depth measurements (and spectral analysis of these samples) are undertaken to gain insight in the transport of sand on the beach.
Description of result Definition of dry sand types with hyperspectral imaging tools proves to be successful. Thematic results will follow.
Deduced sediment transport directions Not available yet.
Publication DERONDE et al. (2001)
Time scale A few years
Space scale The Belgian Coast

Method used STA (sediment trend analysis)
Information on used method Data set of 1110 samples. Sample interval: 3000 m. Important transport vectors used are FB- and FB+. The original McLaren technique only takes into consideration the trends FB- and CB+.
Description of results A STA was carried out on the entire southern North Sea. A distinction can be made between a coastal and an offshore area. In the coastal area the exchange of sediment with offshore is limited; fine sediment seems to be trapped in the coastal area.
Deduced sediment transport directions In the coastal area transport vectors are oriented towards the coast In the offshore area a northeastward transport is dominant In the area of the Flemish Banks, both SW and NE transport directions occur
Publication HAECON (1992a)
Time scale Mega scale (decades)
Space scale Mega scale (100 km)

Method used STA (sediment trend analysis)
Information on used method Data set of 60 samples. Sample interval: 600 m STA was based on the FB+ trend, which is according to the original McLaren technique not a valid trend.
Description of results A STA was carried out on a section of a sandbank (Goote Bank). Results were compared with directions deduced from bedform analysis (small dunes) based on side-scan sonar recordings. Good similarity between two methods in the swale south of the Goote Bank. On the bank differences of 90° exist between the results of the 2 methods.
Deduced sediment transport directions In the swale south of the Goote Bank, residual transport points towards the SW, parallel to the bank. On the bank STA suggests a transport across the bank (from NW to SE); bedforms indicate a transport parallel to the bank's axis (towards the SW).
Publication VAN LANCKER (1993) LANCKNEUS et al. (1993a)
Time scale Macro scale (weeks –months)
Space scale Macro scale (3 km x 4 km)

Method used STA (sediment trend analysis)
Information on used method Data set of 42 (decalcified) samples (taken in May 1993) Sample interval: 500 m Sediment transport patterns deduced from the geometry of large dunes were compared with FB- and CB+ trends. Some reasons for the observed departure are given and include: too small spacing of samples, too small area of analysis, the use of decalcified samples, existence of different sediment transport processes.
Description of results A STA was carried out on a section of a sandbank (Kwinte Bank). Results were compared with directions deduced from bedform analysis (large dunes) based on side-scan sonar recordings. Poor similarity between two methods when using separate transport trend.
Deduced sediment transport directions Both FB- and CB+ trends suggest a sediment transport from the Negenvaam swale towards the bank's crest; large contrasts exist between the results of the two trends on the rest of the study area. Geometry of the large dunes (coinciding with direction of flood peak current) point to a residual sediment transport to the NE.
Publication VANWESENBEECK (1994) VANWESENBEECK and LANCKNEUS (2000)
Time scale Macro scale (weeks –months)
Space scale Macro scale (3 km x 4 km)

Method used STA (sediment trend analysis)
Information on used method Data set of 84 (natural) samples (taken in winter 1989) Sample interval: 500 m All possible trends were analysed; all trends associated with a worsening of the sorting showed little similarity to the sediment transport pattern and can be rejected. The highest degree of similarity to the identified transport patterns was obtained with a combined grain size trend using FB- and CB+.
Description of results A STA was carried out on a section of a sandbank (Kwinte Bank). Results were compared with directions deduced from bedform analysis (small dunes) based on side-scan sonar recordings. Good similarity between two methods when using combined transport vectors
Deduced sediment transport directions STA suggests sediment transport in both swales parallel to the bank's axis and in opposite directions (to the NE in the Kwinte swale and to the SW in the Negenvaam swale). STA indicates as well a component of sediment transport towards the crest of the sandbank; bedforms (small dunes) however suggest a transport parallel to the bank's axis.
Publication LANCKNEUS ET AL. (1992); GAO ET AL. (1994)
Time scale Macro scale (weeks –months)
Space scale Macro scale (3 km x 4 km)

Method used STA (sediment trend analysis)
Information on used method In the framework of a PhD study in the Belgian western near coastal area (Van Lancker 1999), 15 (natural) samples were taken on the southern part of the Middelkerke Bank in November 1996. Sampling interval: 500 m. The combined trend FB- and CB+ was analysed as proposed by Gao & Collins (1992).
Description of results O'Sullivan (1997) carried out a STA. Results were compared with directions deduced from bedform analysis (large dunes) based on bathymetric recordings in November 1996. Good agreement with the dunes along the slope towards the Grote Rede swale. Opposite observations compared to the large dunes higher up the sandbank.
Deduced sediment transport directions STA suggests sediment transport mainly in a NE direction, though the vectors tend to point in a SW direction at the southern extremity of the Uitdiep swale (Flemish Bank region) STA primarily indicates the regional sediment transport in a NE direction.
Publication O'SULLIVAN (1997) VAN LANCKER ET AL. (1997) VAN LANCKER (1999)
Time scale Macro scale (weeks –months)
Space scale Macro scale (1 x 2 km)

Method used STA (sediment trend analysis)
Information on used method In the framework of a PhD study in the Belgian western near coastal area (Van Lancker 1999), 30 (natural) samples were taken on the Ravelingen sandbank in September 1997. Sample interval: 500 m The combined trend FB- and CB+ was analysed as proposed by Gao & Collins (1992).
Description of results Delgado Blanco (1998) carried out a STA. Results were compared with directions deduced from bedform analysis (medium and large dunes) from detailed bathymetric recordings. Good similarity between the two methods when using combined transport vectors.
Deduced sediment transport directions STA suggests sediment transport from the Grote Rede swale towards the sandbank. Veering of the transport east of the sandbank. In the interaction zone with the Flemish Banks, the vectors merely point in a SW direction, but less significant. STA primarily indicates the regional sediment transport in a NE direction.
Publication DELGADO BLANCO (1998) VAN LANCKER ET AL. (1998)
Time scale Macro scale (weeks –months)
Space scale Macro scale

Method used STA (sediment trend analysis)
Information on used method Data set of 90 (natural) samples. In the Westdiep swale, 63 samples were taken in March 1999. These were combined with 27 samples taken in the Broers Bank-Potje coastal system in the framework of biological monitoring (Degraer 1999). Sample interval: variable The combined trend FB- and CB+ was analysed as proposed by Gao & Collins (1992).
Description of results A STA was carried out in the Westdiep and in the shallow coastal system Broers Bank-Potje. Results were compared with directions deduced from bedform analysis from bathymetric recordings (Honeybun 1999) and sediment transport calculations (Van Lancker et al. 2000b). The STA can be explained in terms of the expected sediment transport in the area.
Deduced sediment transport directions STA suggests sediment transport from the Westdiep swale upslope the Trapegeer whilst closer to the coast, vectors merely point in a SW direction. STA indicates as well a winnowing trend from the swale up the sandbank that is mainly tidally driven. Near the coast, the vectors are likely biased by wave refraction and breaking and the higher sediment resuspension during the ebb (SW).
Publication HONEYBUN (1999) VAN LANCKER ET AL. (2000B)
Time scale Macro scale (weeks –months)
Space scale Macro scale (5 x 5 km)

Method used
STA (sediment trend analysis)

Information on used method
Charlet (2001) performed a STA on 63 (natural) samples that were taken in the area east of Zeebrugge in September 2000.
Sample interval: 500 m in the area NW of the Paardenmarkt munition dumpsite; 1 km in the Wielingen area (north of the Paardenmarkt shoal)
The combined trend FB- and CB+ was analysed as proposed by Gao & Collins (1992).

Description of results
Results were compared with single-beam, multibeam and side-scan sonar data in combination with numerical modelling results.
The STA results in 5 zones of sediment transport directions.

Deduced sediment transport directions

Publication
CHARLET (2001)

Time scale
Macro scale (weeks –months)

Space scale
Macro scale

Method used Calculation of residual currents from current meter data 3D numerical modelling
Details on used methodology As an aid to understanding and predicting sediment transport pathways, the magnitude and direction of observed residual currents have been examined at locations around the Middelkerke Bank using current meter data during the period 26 February to 18 March 1993 (CSTAB project, O'Connor (1996)). Moreover, a 3D numerical model (3D tide, wave and wind induced-current computer model) was used to compute the residual current motion in conditions of low wind stress (Williams et al. 2000).
Description of results Residual currents were calculated by removal of 15 tidal constituents from the observed current meter data by spectral analysis. This procedure gave a surge component consisting of low frequency tidal motion and wind driven flow. Measured residual current speeds during the observational period were generally a factor of five times less than the observed average tidal current speeds at the same site. Since the results merely reflect the surge currents and not the long-term residual water movement, they were found inconclusive. Predicted velocity residuals at ¾ depth have been obtained from 3D-bank by simple integration over a number of tidal cycles. Typical results indicate the presence of counter clockwise rotating eddies in the Negenvaam swale to the west of the Middelkerke Bank and in the Uitdiep swale to the east. It is considered that such eddies are a direct consequence of tidal current deflection by the sandbank. The net effect of the two eddies is to drive a clockwise residual circulation of water around the Middelkerke Bank. Enhanced mobilisation and suspension of bed sediments and modifications to bed topography by wave action is likely to occur only in storm conditions.
Deduced sediment transport directions In the Grote Rede and the southern part of the Middelkerke Bank are clearly dominated by residual currents to the NE. On the sandbank itself, the vectors merely point to the NW-N. Along the steep slope, a N-NE residual current is calculated whilst on the eastern stoss slope the vectors point to the SW. In the Negenvaam and Uitdiep swale a counter clockwise motion is obtained. The model did not calculate sediment transport.
Publication O'CONNOR (1996) WILLIAMS (2000)
Time scale Macro scale (1 month)
Space scale Mega scale (10 km: Middelkerke Bank area)

Method used Mathematical model
Details on used methodology A two-dimensional mathematical model was used to reveal the residual tidal currents in the Channel.
Description of results A water flux of about 27.000 m^3/s, for an average tide, flows from the Atlantic to the North Sea.
Deduced sediment transport directions The model did not calculate sediment transport. The residual sediment transport direction, in accordance to the water flux, would be from the Atlantic towards the North Sea.
Publication SALOMON and BRETON (1991)
Time scale Mega scale (years)
Space scale Mega scale (tens of km)

Asymmetry of bedforms
Traces
Suspension measurements
STA
Others

Method used Numerical modelling
Details on used methodology Sediment transport pathways in the Eastern English Channel and the influence of wave activity on sediment transport.
Description of results Grochowski et al. (1993) describe the following results: 1) Tidal action determines largely the long-term transport pattern in the area; this includes a large ebb-dominated mid-Strait region and flood-dominated narrow coastal zones. 2) The main SW and NE winds occasionally overwhelm the tidally induced pattern, with only the SW influencing long-term patterns (by reinforcing the mean movement and shifting the bedload convergence towards the North Sea). 3) There appears to be a genetic relationship between the presence of localised eddying transport paths and the presence of large sandbanks; this requires further investigation, with a model of finer spatial resolution. 4) The superimposed effect of wind-generated surface waves, on the general transport pattern, is negligible. Grochowski & Collins (1994) discuss long-term surface wave records from various parts of the English Channel to determine the percentage of time during a year for which waves disturb the seabed. Most of the bottom sediments are rarely disturbed by waves (< 1% of the time), due to water depth and sediment grain size. The coastal zones (< 30 m), including the embayments, experience significant wave disturbance at the seabed (i.e. > 5-10 %). The general distribution of surficial sediments can be explained in terms of tidally induced processes alone. Even in areas where wave activity is high, fine-grained sediment transport is controlled by the same mechanisms.
Deduced sediment transport directions Tidal action determines largely the long-term transport pattern in the area; this includes a large ebb-dominated mid-Strait region and flood-dominated narrow coastal zones.
Publication GROCHOWSKI et al. (1993a) GROCHOWSKI et al. (1993b) GROCHOWSKI and COLLINS (1994)
Time scale Mega scale (years)
Space scale Mega scale (tens of km)

Method used

Sediment transport modelling

Current and sediment concentration measurements

Details on used methodology

On the basis of current meter data of the Waterways Coast Division (Ministry of the Flemish Community) in combination with sediment and tidal elevation data, a sediment transport model was developed based on the recommendations of Soulsby (1997).

In cooperation with the University of Southampton, an acoustic doppler current profiler was deployed at the Sierra Ventana and in the Baland Bank dune area. The measurements were carried out from the ship with an RDI Workhorse Sentinel 600 kHz ADCP. Meanwhile, water samples were taken and filtered for SPM.

ID	Location	Easting (m)	Northing (m)	Start	End
SV	Sierra Ventana	505817	5697784	1998-09-07 10:24	1998-09-07 17:40
BB	Baland Bank	484371	5675561	1998-09-08 10:15	1998-09-08 23:30

Description of results

The sediment transport calculations showed that the tidal currents are generally competent enough to resuspend the in-situ sediments. Grains up to 210 μm are easily transported throughout the area, whilst grains coarser than 250 μm can only be transported in the swales witnessing a funnelling effect of the current (e.g. Westdiep swale). Under the influence of currents alone, the flood is largely dominant over the ebb, still bedload transport in a SW direction can be initiated, especially in the swales with an ebb-dominated morphology. This situation can be regionally achieved after longer-term periods of even moderate NE conditions.

Deduced sediment transport directions

id	location	qsvrf_avg tonnes/m/dag	qsvrf_dir	id	location	qsvrf_avg tonnes/m/dag	qsvrf_dir
01/60	Grote Rede	4.2	49	03/74	Potje	0.6	62
03/61	Kleine Rede	1.9	53	05/74	WK70 Westdiep	3.2	62
05/62	Westdiep	0.7	55	06/74	Binnen Stroombank	1.3	50
15/65	Ravelingen	0.8	62	07/74	Oostende Bank West	0.2	79
18/66	buitenste Nieuwpoort Bank	0.7	66	08/74	Middelkerke Bank	3.1	60
19/67	Westdiep	4.5	53	01/75	Buiten Stroombank	0.9	79
20/67	Noordpas	0.4	79	09/82	WK57 voor Oostende	1.2	59
28/69	Westdiep	0.1	74	01/87	WK3 Oostduinkerke	0.7	52
31/70	Grote Rede	0.3	72	02/87	West Stroombank	0.4	65
33/70	Noordoost Pas	1.0	59	03/87	Trapegeer	1.3	50
36/71	Voor Oostende	2.2	44	07/87	Smalbank	0.8	67
02/74	Trapegeer	0.2	65	01/88	Voor Oostende E	3.8	61
				02/88	Voor Oostende W	0.9	54

The values obtained are representative for calm weather conditions and are averaged over a spring, mid and neap tide. The amount of suspended load (qs) was calculated on the basis of the Van Rijn (1984) formulae (vrf).

Publication

VAN LANCKER (1999), VAN LANCKER (IN PREP.)

LE COUTURIER et al. (2000)

Time scale

Mega scale (years)

Space scale

Mega scale (20 km)

Method used
Hydrodynamic modelling
Current and sediment concentration measurements

Details on used methodology
In the framework of the OSTC project HABITAT, 2D hydrodynamic modelling was carried out by MUMM (750 m and 250 m grid resolution).

Bottom-mounted acoustic doppler current profiling measurements were carried out along the Trapegeer.

ID	Location	Easting (m)	Northing (m)	Start	End	Type ADCP
TP	Trapegeer	469130	5664757	2000-10-17 10:57	2000-10-19 15:10	RDI Workhorse sentinel 1200 kHz ADCP

Description of results

The hydrodynamical modelling clearly confirms the flood dominance in the area. High NE or flood directed current velocities are calculated in the Westdiep area reaching a maximum value around 0.7 m/s towards the foot of the slope of the Trapegeer sandbank. In the Potje swale, only minor current velocities are calculated.

Deduced sediment transport directions
The modelling did not include sediment transport calculations; though it seems likely that the suspended load would be driven in a NE direction.

Publication
VAN LANCKER ET AL. (IN PREP.)

Time scale
Macro scale

Space scale
Macro scale

Method used Direction of decrease in grain-size
Details on used methodology Grain-size data were based on quantitative studies and on qualitative bottom data.
Description of results A progressive decrease in the grade of the loose sediments takes place in the North Sea. The sediment stream heads from ground of medium-sized sand with some coarse sand (southern Holland) to a mixture of silt with clay (Northern Holland).
Deduced sediment transport directions A decrease in grain-size for the uppermost loose sediments occurs in a Northeastern direction in the Southern North Sea. The sediment variation (from medium sand to fine sand and finally to mud coincides with the transport paths deduced from the asymmetry of sandwaves and would in this case be an indicator of a residual transport path.
Publication STRIDE (1963)
Time scale Mega scale (years)
Space scale Mega scale (tens to hundreds of km)

Method used Grain-size trends
Details on used methodology In the framework of the MASTI Resecused project, three sampling campaigns were carried out to study the distribution of the grain-size parameters of the surficial sediments.
Description of results • There is a clear visual relation between the grain-size and the depth. Coarser sediments rich in $CaCO_3$ occur in the higher parts of the bank while finer sediments are located in the two adjacent swales. • Side-scan sonar and repeated echosounding surveys show that the water depth controls the dune-size. There is a good relation between grain-size and dune-size, but only in the restricted mosaic area. Coarse and very-coarse sand is located in the large dune areas. • The effects of a stormy period are expressed in the surficial grain-size. In periods of fair weather, tidal currents are dominant and build the bedforms in the shallowest parts of the bank. During stormy periods, wind-induced currents and waves affect the upper layer of sediment.
Deduced sediment transport directions The residual sediment transport constitutes a clockwise sense of rotation around the bank as shown by the grain-size parameters distribution and by side-scan surveys.
Publication TRENTESAUX (1993) TRENTESAUX et al. (1994)
Time scale Macro scale (months)
Space scale Macro scale (15 km)

Method used Wreck marks
Details on used methodology Wreck marks are obstacle marks generated by scour and deposition near wrecks, which interrupt tidal current flow. Sand is removed on the net downstream side of the wreck, exposing the coarser substrate as an elongated strip parallel to the peak current flow. Single scour shadows are associated with wrecks that lie parallel to the peak tidal current. When the wreck lies broadside on to the current flow, the wreck marks consist of twin scour shadows.
Description of results Technique NOT used on the Belgian shelf.
Deduced sediment transport directions
Publication CASTON (1979)
Time scale Mega scale (years)
Space scale Macro scale (100 m)

Method used Sediment fraction analysis
Details on used methodology To deduce temporal variations in sediment dynamics, sequential sediment samplings were analysed in more detail. For each sample, the volume percentages of the most common grain-size fractions were individually compared. Care was taken towards the morphological position of each sample as to reduce bias introduced by samples that were not taken at the same location. Such an analysis was carried out for surficial sediments derived from the Nieuwpoort Bank, Stroombank and Baland Bank and from the adjacent beaches from Oostende to Koksijde. The analysis formed part of a sediment- and morphodynamical study based on bathymetric, side-scan sonar and surficial sediment data in combination with sediment transport modelling (Van Lancker 1999).
Description of results For the Nieuwpoort Bank and Stroombank, a consistent bank upward transport trend could be deduced. At the foot of the sandbanks a tidally driven fining upward trend was perceived which was confirmed along the sandbanks and through time. From a level of – 5 m, waves become part of the maintenance mechanism of the sandbank and induce a persistent coarsening of the surficial sediments in a coastwards direction. The coarsest surficial sediments occur at the lee slope. Along the Baland Bank area, a clear fining trend is seen in a NE direction, corresponding with the dominant flood current. NE hydro-meteo conditions are hardly associated with a sediment input; the surficial sediments are coarser as the seafloor merely represents a lag surface. Side-scan sonar imagery shows a rougher texture and calculated sediment volumes in reference areas are minimal. SW conditions significantly enhance sediment transport. The surficial sediments are finer as they are recently deposited; side-scan sonar imagery is less in reflectivity and calculated sediment volumes in reference areas are high. A significant quantitative relation could be established between the sediment volumes (sand) and the ruling hydro-meteorological conditions (Van Lancker *in prep.*).
Deduced sediment transport directions The regional sediment transport is flood-dominated. On the sandbanks, a coastwards dominated trend can be deduced.
Publication VAN LANCKER (1999) VAN LANCKER (in prep.)
Time scale Meso scale
Space scale Macro scale

Method used Turbulence measurements
Details on used methodology The benthic platform TOSCA (transport of sediment under the combined action of waves and currents) was used near the Sierra Ventana (51 25.81 N, 3 5.02 E). A simultaneous recording at 5Hz of horizontal current velocity and direction at 0.35 m, 0.78 m and 1.20 m above the seabed, vertical current speed at 0.78 m above the seabed and suspended sediment concentration at all three heights. Simultaneous high-frequency measurements of water pressure were also obtained at 1.8 m above the bed. The measurements were recorded in hourly bursts of 30 min duration throughout a tidal cycle (15 h). The sampling regime provided a complete set of data for the analysis of both turbulent and macroscale tidal flow patterns.
Description of results The results show that downstream of large topographic features, turbulent and macroturbulent structures exist that differ significantly from a uniform benthic boundary layer (BBL) and that their effects may extend over large distances downstream of bedforms. At the site, large-scale flow modules of turbid and clear waters dominated the BBL related to the shedding of vortices resulting from flow separation processes over upstream large bedforms. The turbulence associated with the large-scale flow motions was characterised by the enhanced participation of outward interactions, which, by carrying turbid flows upward had a significant impact on the maintenance of sediment in suspension and on the subsequent transport of suspended sediment by tidal currents. In such BBL's, the use of eddy correlation or Reynolds shear stress techniques to predict sediment transport may be inadequate. It is likely that the Reynolds stress approach would underestimate the transport of suspended sediment in conditions where the contribution of outward interactions of turbulent flow is increased. The observations underline the importance of obtaining a detailed knowledge of the turbulence structures of the flow before deriving mean-value parameters of the turbulent velocity fluctuations for the prediction of sediment transport processes. The results may explain the poor accuracy of estimates of the local sediment fluxes in flows influenced by bedforms.
Deduced sediment transport directions
Publication LE COUTURIER ET AL. 2000
Time scale Micro scale (hours)
Space scale Macro scale

Method used Integrated studies
Information on used method The following items are dealt with: • Sensitivity analysis of major parameters which influence the efficiency of the dredging process; • The computation of global residual sediment transport patterns to define sediment pathways; • Differential mapping and volumetric calculations for total mass-balance computations; • Soil investigations (sampling, natural radio-activity and vibrocoring); • Dumping processes measurement using radio-active tracers (sand and mud fraction); • Measurement of migration and recycling of dump losses using long-life radio-active tracers (mud traction); • Preliminary environmental assessment of dumping processes
Description of results The acquired knowledge of residual sediment transport mechanisms indicated the existence of a "turbidity maximum area" (T.M.A.) in open sea. Such a T.M.A. governs the sediment accumulation in channels and harbours and consequently the maintenance dredging process management.
Deduced sediment transport directions
Publication MALHERBE (1991)
Time scale Mega scale (years)
Space scale Mega scale (several km)

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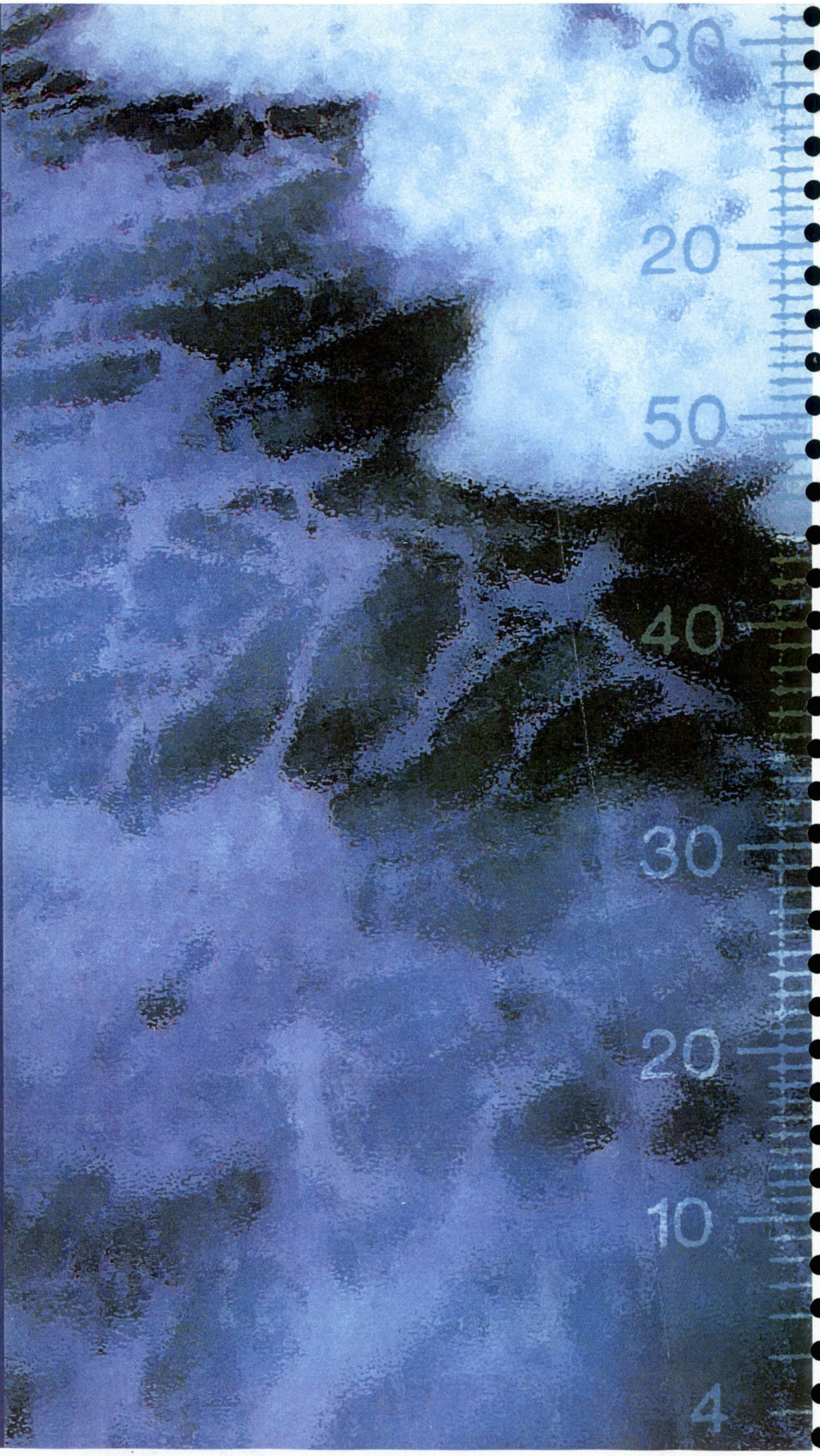

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